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Topic

Improving Streets for Sustainable Neighborhoods in Chinese Urban Villages

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An Investigation of the Role of Neighborhood Street Planning in Promoting Individual Mental Well-being and Daily Mobility

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Abstract

Urban Villages (UVs) are a product of rapid urbanization, which have high-density physical environments and complex street networks that impact residents' daily lives. As a fundamental element of urban life, the neighborhood streets affect the quality of life of urban residents. However, the existing one-size-fits-all approach to urban street planning often lacks resilience and adaptability in China, failing to meet the needs of high-density UVs and enhance the residential environment and social sustainability of these areas.

This study aims to explore the use of innovative street measurement methods to quantify the street environments in Shenzhen's UVs and their interactions with street users. By systematically evaluating innovative street metrics from both subjective and objective perspectives, this research focuses on how these methods can identify street spaces and, based on the results, optimize the physical environment and ambiance of streets to encourage residents' active travel, enhance mental well-being. The research employs a range of advanced technological methods, including spatial syntax analysis, deep learning, and social media data analysis, while refining the concept of innovative streets and their applicability in UV settings.

This dissertation, based on an in-depth investigation of high-density urban village street environments, proposes the concept of "innovative streets." The core of this concept lies in employing diverse quantitative methods to comprehensively examine the mobility and livability of streets. Unlike traditional single-dimensional or macro perspectives, "innovative streets" integrate top-down and bottom-up evaluation frameworks while combining subjective perceptions with objective indicators to achieve a multi-layered characterization of street environments. At the micro-level, the study utilizes technologies such as street view images with semantic segmentation, drone monitoring, and multi-object tracking to precisely capture key spatial attributes of streets, including width, building height, and greenery coverage. At the macro-level, the research leverages social media big data to analyze residents' evaluations of street spaces and their sense of well-being. By integrating this multi-source information with European street measurement methodologies, the dissertation further elucidates the mechanisms by which street landscapes influence residents' mental health and daily mobility behaviors.

Findings of this research include:

Firstly, through qualitative analysis, the dual function of streets as both conduits for transportation and social interaction was revealed. The qualitative analysis emphasized the importance of streets in social interaction, particularly in high-density, low-income UVs, where streets serve as primary spaces for resident communication and interaction. Quantitative analysis provided detailed data on street width, building heights, and green coverage through drone monitoring and multi-target tracking technology. This combination of subjective and objective methods validated the hypotheses of the qualitative analysis and expanded the understanding of street environments.

Secondly, this study attempted to apply the street space measurement methods used in Düsseldorf,

Europe, to the UVs of Shenzhen and tested their effectiveness through empirical research. The results underscored the necessity of collecting street environment perceptions from a pedestrian's perspective (rather than a vehicular perspective) and highlighted that street measurement methods need to be adjusted according to the specific environmental c ontext. However, the findings generally support that a diverse streetscape encourages walking, though geographical heterogeneities exist in aspects like street greening and on-street parking.

Thirdly, the research found that enhancing street cleanliness and optimizing public facilities can improve residents' positive sentiments and life satisfaction. Maintaining a rich functional diversity in UVs often radiates more urban areas, providing convenience in daily life. Increasing public transportation infrastructure near UVs and implementing traffic calming measures within UVs can enhance circulation both within and around the area. Additionally, optimizing business models for small-scale economies within UVs, such as transitioning to e-commerce, can help reduce spatial stigmatization by boosting the economy and increasing community cohesion.

Fourthly, we observed that UV residents are particularly sensitive to street width but less so to pedestrian density on the streets. Where street widths permit, more streetside buffer spaces are needed, which can serve as storage spaces as well as social spaces, enhancing neighborhood vitality. Our study found that moderate building density and proper building proportions (55%-65%) enhance pedestrian experiences and street vitality. However, due to the high-density physical environment of UV streets, increasing street greening might compress the limited street space, affecting commuting. The combination of drones and deep learning technologies used in this study also addressed the limitations of a bottom-up human perspective.

In conclusion, this study proposed an innovative street measurement framework that integrated subjective and objective assessments while combining macro and micro perspectives, offering valuableinsights into the development of people-centered street concepts in UVs. However, focusing on UVs asrepresentative cases of informal settlements had its limitations due to their unique geographicallocation, cultural background, and rapid urbanization model, which constrained the global applicabilityof the findings. Furthermore, although social media texts and open big data sources were utilized for analysis, these data sources were insufficient to comprehensively capture long-term dynamic processesand might have suffered from biases or inadequate spatiotemporal coverage. Lastly, the study's singular focus on the perspective of streets might have overlooked the synergistic relationships with other urbanspatial elements, making it challenging to fully reflect the interconnectedness and interactions betweenUVs and broader urban systems. Future research should refine resident-centered street measurementmethods and explore their applicability in diverse urban environments to support sustainable urbantransitions.

Kurzzusammenfassung

Urban Villages (UVs) sind ein Produkt der raschen Urbanisierung und zeichnen sich durch dichte bauliche Strukturen und komplexe Straßennetze aus, die das tägliche Leben der Bewohner beeinflussen. Als ein grundlegender Bestandteil des städtischen Lebens wirken sich Nachbarschaftsstraßen maßgeblich auf die Lebensqualität der Stadtbewohner aus. Der derzeit in China vorherrschende, einheitliche Ansatz in der städtischen Straßenplanung weist jedoch häufig Mängel in Bezug auf Resilienz und Anpassungsfähigkeit auf, wodurch er den speziellen Bedürfnissen von hochdichten UVs nicht gerecht wird und somit deren Wohnumfeld und soziale Nachhaltigkeit nicht verbessert.

Diese Studie zielt darauf ab, innovative Methoden zur Straßenvermessung zu untersuchen, um die Straßenumgebung in den UVs von Shenzhen zu quantifizieren und ihre Interaktion mit den Nutzern zu erfassen. Durch eine systematische Bewertung von innovativen Straßenmetriken aus sowohl subjektiver als auch objektiver Perspektive legt diese Forschung den Schwerpunkt darauf, wie diese Methoden zur Identifizierung von Straßenräumen beitragen können, um basierend auf den Ergebnissen die physische Umgebung und Atmosphäre der Straßen zu optimieren. Dies soll die aktive Mobilität der Bewohner fördern und ihr psychisches Wohlbefinden steigern. Die Forschung setzt dabei fortschrittliche Technologien ein, darunter räumliche Syntaxanalyse, Deep Learning und die Analyse von Daten aus sozialen Medien, um das Konzept der innovativen Straßen zu verfeinern und dessen Anwendbarkeit in UV-Kontexten zu erforschen.

Diese Dissertation untersucht die Straßenumgebungen von hochdichten urbanen Dörfern und entwickelt das Konzept der „innovativen Straßen“. Der Kern dieses Konzepts liegt in der Anwendung diverser quantitativer Methoden, um die Mobilität und Lebensqualität von Straßen umfassend zu analysieren. Im Gegensatz zu traditionellen, eindimensionalen oder makroperspektivischen Ansätzen integrieren „innovative Straßen“ Top-Down- und Bottom-Up-Bewertungsrahmen und kombinieren subjektive Wahrnehmungen mit objektiven Indikatoren, um eine vielschichtige Charakterisierung von Straßenumgebungen zu ermöglichen. Auf Mikroebene nutzt die Studie Technologien wie Straßenbildaufnahmen mit semantischer Segmentierung, Drohnenüberwachung und Multi-Objekt-Tracking, um räumliche Schlüsselmerkmale von Straßen präzise zu erfassen, darunter Breite, Gebäudehöhen und Begrünungsanteil. Auf Makroebene werden Social-Media-Daten analysiert, um die Bewertungen der Bewohner zu Straßenräumen und deren Wohlbefinden zu untersuchen. Durch die Integration dieser multi-quellenbasierten Informationen mit europäischen Straßenmessmethoden wird in der Dissertation weiter beleuchtet, wie Straßenlandschaften die mentale Gesundheit und das tägliche Mobilitätsverhalten der Bewohner beeinflussen.

Zu den Forschungsergebnissen gehören:

Erstens zeigte die qualitative Analyse die doppelte Funktion von Straßen als Transportwege und Räume sozialer Interaktion auf. Die qualitative Analyse unterstrich die Bedeutung von Straßen für soziale Interaktionen, insbesondere in hochdichten, einkommensschwachen UVs, wo Straßen als primäre

Räume für die Kommunikation und Interaktion der Bewohner dienen. Die quantitative Analyse lieferte detaillierte Daten zur Straßenbreite, Gebäudehöhe und Grünflächenbedeckung durch den Einsatz von Drohnenüberwachung und Multi-Target-Tracking-Technologie. Die Kombination von subjektiven und objektiven Methoden validierte die Hypothesen der qualitativen Analyse und erweiterte das Verständnis der Straßenumgebungen.

Zweitens versuchte diese Studie, die in Düsseldorf, Europa, angewandten Straßenraummessmethoden auf die UVs von Shenzhen zu übertragen und testete deren Wirksamkeit durch empirische Forschung. Die Ergebnisse betonten die Notwendigkeit, die Wahrnehmung der Straßenumgebung aus der Perspektive der Fußgänger zu erfassen und zeigten, dass Straßenmessmethoden an den spezifischen Kontext angepasst werden müssen. Im Allgemeinen unterstützen die Ergebnisse die Annahme, dass eine vielfältige Straßenlandschaft das Gehen fördert, obwohl geografische Unterschiede in Bezug auf Straßengrün und Parken an der Straße bestehen.

Drittens stellte die Forschung fest, dass die Verbesserung der Straßenreinheit und die Optimierung öffentlicher Einrichtungen die positiven Gefühle und die Lebenszufriedenheit der Bewohner steigern können. Eine funktionale Vielfalt in UVs strahlt oft auf andere städtische Gebiete aus und bietet Bequemlichkeit im Alltag. Der Ausbau der öffentlichen Verkehrsinfrastruktur in der Nähe von UVs und die Umsetzung von Verkehrsberuhigungsmaßnahmen können die Zirkulation innerhalb und außerhalb der Gebiete verbessern. Darüber hinaus kann die Optimierung von Geschäftsmodellen für kleine Wirtschaften, wie der Übergang zum E-Commerce, dazu beitragen, die räumliche Stigmatisierung zu reduzieren, indem die Wirtschaft gestärkt und der Gemeinschaftszusammenhalt erhöht wird.

Viertens wurde beobachtet, dass die Bewohner von UVs besonders empfindlich auf die Straßenbreite reagieren, weniger jedoch auf die Fußgängerdichte auf den Straßen. Wo es die Straßenbreite zulässt, sind mehr Pufferzonen entlang der Straßen erforderlich, die sowohl als Lagerräume als auch als soziale Räume dienen können, um die Vitalität der Nachbarschaft zu steigern. Unsere Studie ergab, dass eine moderate Gebäudedichte und angemessene Gebäudeproportionen (55%-65%) das Fußgängererlebnis und die Vitalität der Straßen verbessern. Aufgrund der hohen Dichte der physischen Umgebung in UV-Straßen könnte jedoch die Erhöhung des Straßengrüns den ohnehin begrenzten Straßenraum komprimieren und den Pendelverkehr beeinträchtigen. Der Einsatz von Drohnen und Deep-Learning-Technologien in dieser Studie überwand auch die Einschränkungen einer bottom-up menschlichen Perspektive.

Abschließend schlug diese Studie einen innovativen Rahmen für die Straßenmessung vor, der subjektive und objektive Bewertungen integrierte und dabei makro- und mikroskopische Perspektiven kombinierte. Dieser Ansatz bot wertvolle Einblicke in die Entwicklung menschenzentrierter Straßenkonzepte in UVs. Allerdings hatte die Fokussierung auf UVs als repräsentative Fälle informeller Siedlungen ihre Grenzen, da ihre einzigartige geografische Lage, kulturelle Prägung und das schnelle Urbanisierungsmodell die globale Anwendbarkeit der Ergebnisse einschränkten. Darüber hinaus waren die verwendeten sozialen Mediendaten und offenen Big-Data-Quellen zwar nützlich, jedoch unzureichend, um langfristige dynamische Prozesse umfassend zu erfassen, und könnten von Verzerrungen oder unzureichender räumlich-zeitlicher Abdeckung betroffen gewesen sein. Schließlich könnte sich der einseitige Fokus der Studie auf die Straßenperspektive als unzureichend erweisen, um die synergistischen Beziehungen zu anderen urbanen Raumelementen vollständig zu berücksichtigen, was es erschwerte, die Vernetzung und Wechselwirkungen zwischen UVs und umfassenderen urbanen Systemen vollständig abzubilden. Zukünftige Forschungen sollten bewohnerzentrierte Straßenmessmethoden weiterentwickeln und deren Anwendbarkeit in verschiedenen urbanen Umfeldern untersuchen, um nachhaltige urbane Transformationen zu unterstützen.

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Gemäß § 11 der Promotionsordnung der Fakultät Raumplanung der Technischen Universität Dortmund erkläre ich folgende Punkte:

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Ort und Datum

Jin Rui

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List of Abbreviations

UV	Urban Villages
FAR	Floor Area Ratio
SVI	Street view image
FS	Formal settlement
NLP	Natural Language Processing
BERT	Bidirectional Encoder Representations from Transformers
IoT	Internet of Things
GIS	Geographic Information Systems
CV	Computer Vision
SDG	Sustainable Development Goals
sDNA	Spatial Design Network Analysis
OSM	Open Street Map
PSI	Positive Sentiment Index
GBDT	Gradient Boosting Decision Trees
DCNNs	Deep Convolutional Neural Networks
GWR	Geographically Weighted Regression
MGWR	Multiscale Geographically Weighted Regression
POI	Point of Interest

Chapter 1

Background

1.1 Migrant population in the process of urbanization and settlement strategies in Shenzhen

The advancement of globalization and urbanization in developing countries, has led to a massive migration of populations from rural to urban areas (Li, 2012). This phenomenon is reflected not only in the increased mobility of populations but also in the transformation of urban spaces (Bertolini, 2020). The rapid increase in the migrant population, especially new immigrants from rural areas, has created similar urban spatial forms globally, such as the slums in South America and India, UVs and basements in China, and low-income enclaves in Europe and America (Yang et al., 2021; Zhu, 2016). The emergence of these informal urban spaces reflects common issues in the urbanization process under globalization (Campos et al., 2022).

The rapid growth of Chinese cities is driven by the influx of migrant workers, the largest such movement in compressed time in history (Roulleau-Berger, 2021). Migrant populations, led by rural migrant workers, often flock to cities in search of employment opportunities (Zhu, 2016). Thus, the migrant labor force from rural areas becomes the backbone of export-oriented industries, manufacturing, and low-end service sectors in urban areas (Lin et al., 2011). The population flow to cities not only continues but is exacerbated by economic reforms that emphasize private enterprise, competition, and foreign investment (Liang et al., 2021). According to the data from the Seventh National Population Census, China's migrant population reached 376 million in 2020, an increase of 150 million compared to 2010.

In the context of rapid urbanization and industrialization, the migrant population primarily resides in informal residential areas of cities, such as UVs and basements (Zhu, 2016; Lin et al., 2011). Informal residential areas are a global phenomenon; according to the United Nations Human Settlements Program data in 2020 (Mboup, 2017), it is estimated that about 25% of the global population (approximately 1 billion people) live in such areas. Although these areas provide housing, they often have poor living conditions and lack necessary infrastructure and public services (Cui et al., 2023). Moreover, these areas often face challenges such as environmental issues, security problems, and social exclusion (Guo et al., 2017). For the migrant population, these areas are not only transitional zones for integrating into urban life but also hotspots for social risks and problems (Van Oostrum, 2022). As a special phenomenon in China's urbanization process, UVs carry a large migrant population and are closely linked to the city's development (Hao et al., 2012; Liu et al., 2010; Wu et al., 2013). In rapidly developing cities like Shenzhen, the renewal and transformation of UVs are key to optimizing urban space, enhancing overall urban functionality, and improving living quality. The urban transformation plan is not only an innovation in the spatial and resource utilization of UVs but also a beneficial attempt to address the residential issues of the migrant population and urban renewal globally (Campos et al., 2022).

Located in the southern part of Guangdong Province, Shenzhen is a national economic center and an innovative city. According to the ”Guangdong Statistical Yearbook (2022),” by the end of 2022, Shenzhen was divided into 10 districts, covering a total area of 1997.47 square kilometers, with a permanent population of 17.66 million (Wu et al., 2024). Shenzhen faces the issue of excessive land development intensity in its urban expansion, where the land development intensity has reached 50%, exceeding the international warning line of 30% (Cheng et al., 2023). The scarcity of land resources has become the main bottleneck for Shenzhen's development. Facing this challenge, Shenzhen has shifted its focus to urban renewal, emphasizing the utilization and transformation of existing land resources to promote sustainable urban development (Pan and Du, 2021). The ”Shenzhen Housing Development 14th Five-Year Plan” emphasizes improving housing quality in the precision renovation stage, aiming to create residential neighborhoods that are convenient, well-equipped, and comfortable. This marks a new direction for Shenzhen's UV transformation, focusing more on protecting the original neighborhood structure and culture while enhancing the efficiency and quality of urban space utilization (Rui et al., 2024). The plan also proposes promoting organic renewal of UVs and green building to improve living environments. These data and policy measures showcase Shenzhen's strategies in urban planning and management to address challenges brought by rapid development (Xu et al., 2024).

1.2 The urgency of transforming UV streets: mobility and livability dimensions

As a special phenomenon in the process of urbanization, the street environment of UVs has significant deficiencies in terms of mobility and livability, which directly affect the daily active travel behavior and the well-being of the residents (Bertolini, 2020; Huang et al., 2022; Li et al., 2014b). These deficiencies not only bring inconvenience to residents' daily lives but also exacerbate social inequality within cities and hinder sustainable urban development (Niu et al., 2021; Chung, 2010; Wong et al., 2024). Therefore, the transformation of streets in UVs is of high necessity.

1.2.1 Lack of mobility and safety issues in active travel

The street networks in UVs are often highly irregular and feature a mix of various forms of traffic, leading to extreme inconvenience for residents' daily travel (Wang et al., 2009). Narrow streets and imperfect traffic organization result in safety hazards for active travel modes such as walking and cycling (Yu et al., 2019). Pedestrians and non-motorized vehicles often share the road with motorized vehicles, lacking clear separation and guidance, which not only increases the risk of traffic accidents but also causes confusion for residents when choosing their mode of travel (Poon, 2017). This street environment poses a structural obstacle to active travel.

In this context, residents of UVs are unable to fully enjoy the mobility convenience that high-density communities are supposed to offer (Tan et al., 2019). The inefficient connectivity and chaotic patterns of streets limit residents' access to urban resources, especially during rush hours when narrow streets become traffic bottlenecks (Tiwari, 2002). The travel time for residents is unnecessarily prolonged, increasing commuting costs and directly affecting their quality of life and work efficiency. This lack of effective mobility not only constrains the daily lives of residents but also impedes the development and integration of the entire community.

1.2.2 Lack of livability and mental health risks

Another prominent issue in UV environments is the lack of livability, which is not only reflected in the deficiency of material conditions but also in the low levels of mental health and life satisfaction among residents (Van Oostrum, 2022; Tan et al., 2019). High-density buildings, lack of greenery, and public spaces contribute to a sense of oppression and enclosure in UVs (Xu et al., 2024). The monotony and lack of vibrancy in the street landscape make it difficult for residents to experience joy and satisfaction in their daily lives.

Moreover, the streets in UVs often lack public facilities and spaces for community activities (Li et al., 2014b; van Oostrum, 2020a), which weakens the social functions of the community and leaves residents' needs for leisure and entertainment unmet. Residents are confined to narrow street spaces, lacking contact with nature and open areas, leading to increased feelings of isolation and anxiety (Chung, 2010). The interaction and cohesion of the community are weakened, reducing residents' sense of belonging and safety in the environment, affecting their overall mental well-being.

This environment of inadequate livability keeps the living conditions and mental health of UV residents at a consistently low level, hindering their active participation in the community and city. Residents find it difficult to find suitable opportunities for relaxation and social interaction in their daily lives, leading to the accumulation of mental stress, which could potentially trigger social issues (Brindley, 2003). This lack of livability directly challenges urban social harmony and stability, necessitating urgent attention.

1.3 Introducing innovative streets in UVs

UV streets, as unique and complex micro-spaces within cities, exhibit a characteristic of being both chaotic and orderly. These streets are often surrounded by densely packed buildings, lacking systematic planning and management, resulting in traffic congestion, safety hazards, and insufficient greenery (Hao et al., 2011; Li et al., 2021a). The streets' functions are typically limited, impacting residents' daily mobility and mental well-being. However, these streets also serve as vital venues for social interactions and commercial activities, reflecting a distinct urban lifestyle that challenges traditional urban planning perspectives on street environments (Li et al., 2015). Traditional research has predominantly focused on the physical characteristics of UV streets, such as road width and greenery coverage, using static quantitative indicators to deconstruct their features (Xu et al., 2024; van Oostrum, 2020a; Shen et al., 2023). This approach often overlooks the complexity of streets as dynamic, multidimensional interactive spaces. An over-reliance on static data makes it difficult to reveal the interaction between street environments and residents' behaviors, limiting the ability to explain how streets impact residents' mental health and social interactions.

The working definition of "innovative streets" is rooted in its quantitative framework, which integrates top-down and bottom-up methodologies while synthesizing macro- and micro-level analyses with subjective and objective measurements. This definition conceptualizes streets' physical attributes and social functions as being inextricably linked to residents' experiences. By incorporating macro-level spatial data—such as POI and FAR (top-down)—alongside micro-level observations derived from drone imagery, street view sampling, social media data,(bottom-up), innovative streets capture both the structural characteristics of street spaces and behaviors of residents.

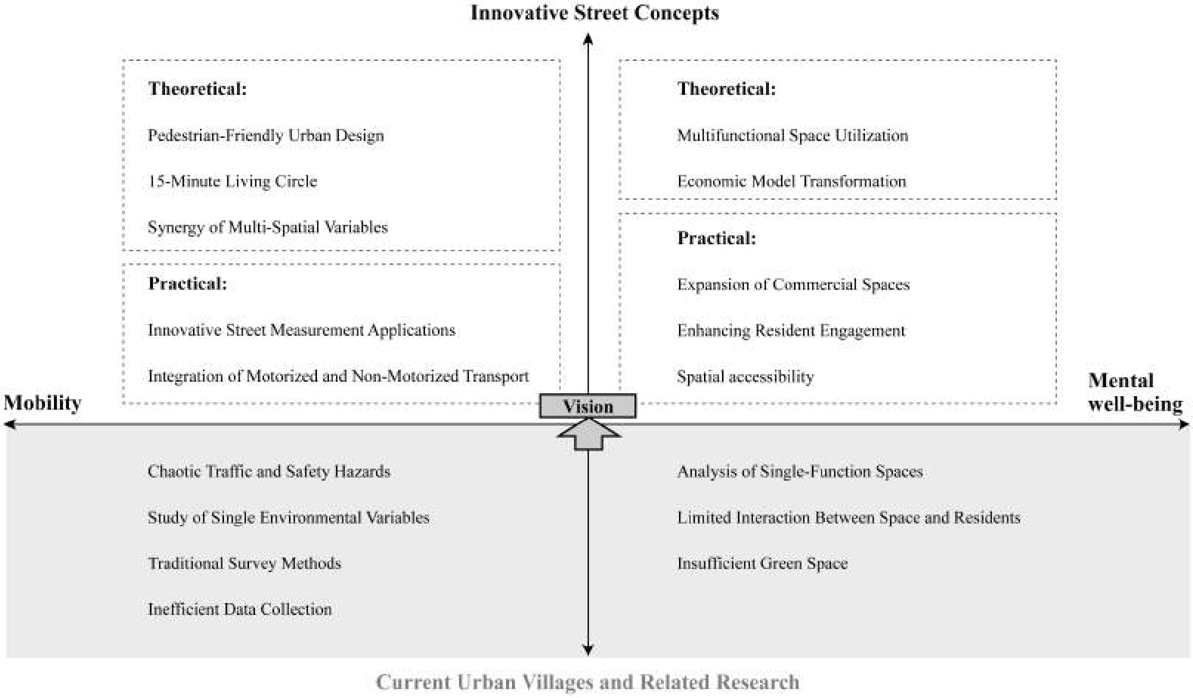


Figure 1.1: Using the innovative street concept in UV streets to enhance mobility and residents' mental well-being.

These methods uncover the nuanced patterns of street usage and perception. Through this multi-tiered and multidimensional quantification, innovative streets elucidate the intricate relationships between street morphology, social cohesion, and public health, thereby providing a robust analytical foundation for policymaking and design interventions.

I initially assessed the potential benefits and necessity of applying the Innovative Streets concept in UVs. However, it is important to note that the actual implementation and impact of this working concept in such contexts remain uncertain. In the subsequent analysis and discussion sections, I will revisit this concept to evaluate whether these initial predictions hold true.

The application of innovative streets in UVs is first reflected in the focus on the synergy of multiple spatial variables. This involves not only considering the physical attributes of the streets but also understanding the relationship between the streets' macro and micro physical properties and residents' behavior and mental and physical health. For example, research that starts from the residents' perspective to improve the micro-level street environments in UVs can promote the use of multifunctional spaces. UV streets can then evolve from simple traffic passages to multifunctional platforms for resident interaction, commercial activities, and social exchanges. This design concept aligns with the construction of the "15-minute living circle," aiming to provide residents with convenient services, thereby enhancing their quality of life and mental health.

Secondly, the innovative street concept's application in UV environments emphasizes methodological innovation. Traditional studies often rely on static surveys, which fail to fully capture the dynamic characteristics of UV streets. In contrast, innovative street research introduces advanced measurement and data analysis tools, such as innovative street measurement applications, which can monitor and analyze street usage in real-time. These technological tools enable more accurate identification of changes in UV streets across different temporal and spatial scales, providing data support for the formulation of more effective improvement strategies.

Under a framework that combines theory and practice, innovative street research offers concrete practical solutions for the development of UVs. For instance, by considering commercial expansion within limited street spaces, it can stimulate regional economic vitality. Additionally, strategies that enhance resident participation can promote interaction between residents and the street environment, increasing their sense of belonging and satisfaction with the community. These practical measures can improve the physical environment of UVs and, to some extent, alleviate social issues such as limited green spaces and the underutilization of single-function spaces.

Moreover, applying the innovative street concept in UVs places special emphasis on residents' mental health and well-being. By creating multifunctional, multi-layered street spaces that encourage daily activities and social interactions, innovative street research focuses on how spatial design influences residents' mental states. This people-centered design philosophy is crucial for the sustainable development of UVs, contributing to an improved quality of life for residents on both material and mental levels.

In conclusion, applying the innovative street concept in UV environments provides a new perspective for improving the complex street environments in these areas. By integrating multi-dimensional spatial variables, introducing advanced measurement methods, and closely linking theory with practice, this concept has the potential to transform UVs from single-function, disordered areas into multifunctional, interactive urban spaces, thereby enhancing residents' quality of life and community well-being.

1.4 Research objectives and questions

This study aims to explore the use of innovative street measurement methods to quantify the street environment in UVs in Shenzhen and examine its interaction with street users. By systematically evaluating these innovative measurement methods from both subjective and objective perspectives, this research focuses on how these methods can identify street spaces. Based on the findings, the study seeks to optimize the physical environment and atmosphere of streets to encourage residents' active travel, enhance mental well-being, and promote the overall sustainable development of communities. Based on this research objective, the study proposes four research questions:

Research question 1: How can we access the physical and perception dimensions of streetscape environment?

In assessing the quality of street environment, research typically employed subjective, objective, or a combination of both methods (Qiu et al., 2022). Subjective assessments primarily relied on perceptual data collected through surveys and interviews (Ogawa et al., 2024), while objective assessments depended on quantitative data gathered from GIS (Sheikh-Mohammad-Zadeh et al., 2022). Essentially, neighborhood environments represented an amalgam of physical, social, and economic elements. Previous studies predominantly utilized objective indicators through comparative analysis to explore how street environments influenced other urban phenomena (Voordeckers et al., 2021). Conversely, the concept of ”sense of place,” particularly in relation to the perceived quality of micro-scale street design, had long been neglected due to a lack of efficient assessment methods and large-scale data (Shamai and Ilatov, 2005). Traditionally, field observations had been the standard method for collecting subjective data on street design quality. This approach required specially trained researchers to conduct on-site assessments, making it both time-consuming and costly, and challenging to implement on an urban scale (Chen et al., 2022a; Kang et al., 2020).

This research question aims to address three key research gaps: Firstly, prior research largely relied on objective indicators to characterize street quality, such as the number of trees, canopy size, and tree canopy coverage using GIS data (Voordeckers et al., 2021). More recently, some studies had used CV to extract street view pixels as view indices to identify street trees, sky, and building views (Xu et al., 2022). However, both GIS data and street view indices failed to fully capture the subtle human experiences on the street. Perception is a highly subjective process of acquiring sensory information (Sun et al., 2023). Subjective measurements from perceptual issues could provide a more complete understanding of human behavior (Qiu et al., 2021). While previous studies measured subjective aspects related to crime (Hanslmaier, 2013), discussions on resident mobility and subjective well-being were less frequent. Other critical concepts in street planning, such as imageability and enclosure, had not been incorporated into these studies (Ewing and Handy, 2009).

Secondly, there was a scarcity of locally collected data describing the perceptions of residents in mainland China regarding street landscapes. The few studies that included human perception were primarily based on Place Pulse data (Larkin et al., 2021). While Place Pulse provided the largest global dataset of urban perceptions, its application to other contexts was contingent upon the availability of data, excluding SVI from mainland China. Street scenes in mainland China varied significantly and might exhibit considerable differences (Qiu et al., 2022).

Moreover, even within objective measurement standards, a comprehensive integration of cognitive aspects had consistently been undervalued. Only a few visual elements, such as trees, sky, and buildings, had been used (Gong et al., 2018). Other elements crucial to urban design research, such as business hours and shop sizes, had been overlooked.

Addressing these research deficiencies, this research aims to develop a comprehensive street assessment system that combines subjective perceptions with objective indicators. Additionally, by integrating user-generated content from digital platforms like social media, real-time feedback and emotional tendencies of residents regarding street environments can be accessed, providing evidence of how well street designs meet residents' needs. Furthermore, combining these subjective data with objective environmental measurements can help urban planners and designers understand how different design elements affect residents' daily experiences, thereby optimizing design decisions and promoting the development of more inclusive and humane urban spaces.

Research question 2: How can we selectively borrow and moderately adapt the methodological workflow of streetscape measurement from Europe for use in the street studies of UVs?

Düsseldorf, Germany, known for its pedestrian-friendly environment, has accumulated valuable planning practices in enhancing street mobility and walkability. To what extent can these practices serve as a reference for the renewal of Shenzhen's UVs, enabling adaptable quantitative studies of different street types on comparable dimensions? Specifically, can the methods used in Germany to measure walkability, walking potential and pedestrian volume be partially transferred to UVs, or is it possible to modify these quantitative approaches based on German experiences and the complex environments of UVs to better suit the spatial and mobility characteristics of different scenarios?

The importance of this inquiry lies in the increasing prominence of transportation and community environment optimization needs within urbanizing UVs. As urban governance shiftsfrom large-scale demolitions to more refined micro-adjustments, improving residential areas and their streets has become a focal point of current planning practices. Adapting Germany's quantifiable tools forwalkability and connectivity for local contexts not only helps identify the functionality and social valueof UV streets but also provides a more data-supported approach for subsequent planning interventions.

However, given the significant differences in spatial features, population density, and social culture between German streets and UVs, it is necessary to develop differentiated measurement methods or even to create specific quantitative approaches for UVs themselves to more comprehensively quantify different street environments. This implies that German streetscape quantification methods may not be directly applicable, aligning with the planning logic that acknowledges spatial differences in localcontexts.

Adjusting and evaluating German street planning experiences from an international perspective can broaden urban planners' insights and drive innovation in urban village street planning. This approach also offers valuable case studies and theoretical support for the sustainable governance of informal settlements, with relevance to rapidly urbanizing regions and cities in the Global South.

Research Question 3: How does the built environment of UVs affect residents’ positive sentiments to promote residents’ well-being and spatial livability?

The third research question focuses on exploring the relationship between the built environment of UVs and the mental well-being of their residents. Specifically, it investigates how improvements to the street environment of UVs at a micro-scale can enhance residents’ positive sentiments and life satisfaction. The formulation of this research question is primarily influenced by several practical issues. Firstly, UVs epitomize the unequal exchange under the urban-rural dual system, which results in the marginalization of UV residents in terms of legal rights and social services. This prolonged marginalization may lead to a perceived lack of social support, increasing mental stress (Guo et al., 2017). Secondly, UVs are often characterized by high-density living conditions with insufficient public spaces and green areas. Such high density and crowded living conditions may lead to higher levels of stress among residents and increase the likelihood of social conflicts (Wu et al., 2013). Thirdly, UVs are seen as unregulated assets, where informality and the resultant instability may negatively affect residents’ sense of security and mental well-being. As transitional neighborhoods, residents of UVs may face confusion regarding their identity (Eckenwiler, 2018; Liu et al., 2017).

Exploring the third research question is of paramount importance as it relates to the United Nations’ Sustainable Development Goal 11: to make cities and human settlements inclusive, safe, resilient, and sustainable (Rosa, 2017). This includes supporting positive economic, social, and environmental links by providing adequate, safe, and affordable housing and basic services and improving the living conditions of residents in UVs.

This research question contributes to a deeper understanding of the application of emotional geography in urban settings. By analyzing the emotional responses of UV residents and their interactions with their environment, insights can be provided for the planning of UVs and other informal settlements.

Research Question 4: How does the daily mobility of UV residents contribute to urban mobility, and what is its association with the micro-scale streetscape of UVs?

Macro-level studies reveal broad trends and potential issues in urban development but are insufficient for capturing the specific daily travel details of particular groups and their interactions with urban spaces (Czepkiewicz et al., 2020; Wang and Hess, 2021). In contrast, micro-level research concentrates on the specific behaviors of individuals or particular groups within the urban context. Here, the focus is on the daily commuting habits of residents in UVs. This type of study examines individuals’ travel choices, preferences, and route decisions, as well as the relationship between these decisions and the micro-environment of the streets (Mertens et al., 2016; Ma et al., 2021). Through detailed micro-analysis, research can intricately depict the commuting behaviors of specific populations in particular settings, thereby providing precise and effective support for targeted UV street planning strategies.

This research question focuses on exploring the relationship between residents' daily travel preferences and the micro-urban landscape of UV streets. The formulation of this question is based on the recognition that the UV streets, as microcosms of urban life, have street landscapes that could influence the residents' daily travel behaviors. UV streets typically feature distinct architectural patterns (such as handshake buildings and tube houses), narrow spatial configurations, and vibrant public space activities, all of which may impact pedestrian behaviors and everyday mobility (Gao et al., 2020). Understanding the connection between the streetscape of these high-density, informal residential areas and the daily mobility of residents can guide the transformation of street spaces to better meet the actual needs of the neighborhood, thereby promoting efficient space utilization and neighborhood integration.

Considering the diversity of residents' identities and daily purposes, the use of UV streets exhibits differences. These differences are not only reflected in residents' daily mobility habits but also in the efficiency and manner of street space utilization (Liu et al., 2020a). The main differences are manifested in several aspects: firstly, in the choice of mobility modes, where residents may prefer walking, cycling, or using public transport. Secondly, in the use of street functions, where different individuals may use streets as places for gathering, shopping, or dining. Additionally, the efficiency of daily mobility is another aspect of differentiation, with new migrant workers possibly favoring main streets due to unfamiliarity with the street layout, whereas local residents may utilize alleyways more, thus demonstrating different efficiencies in street space use.

1.5 Thesis structure

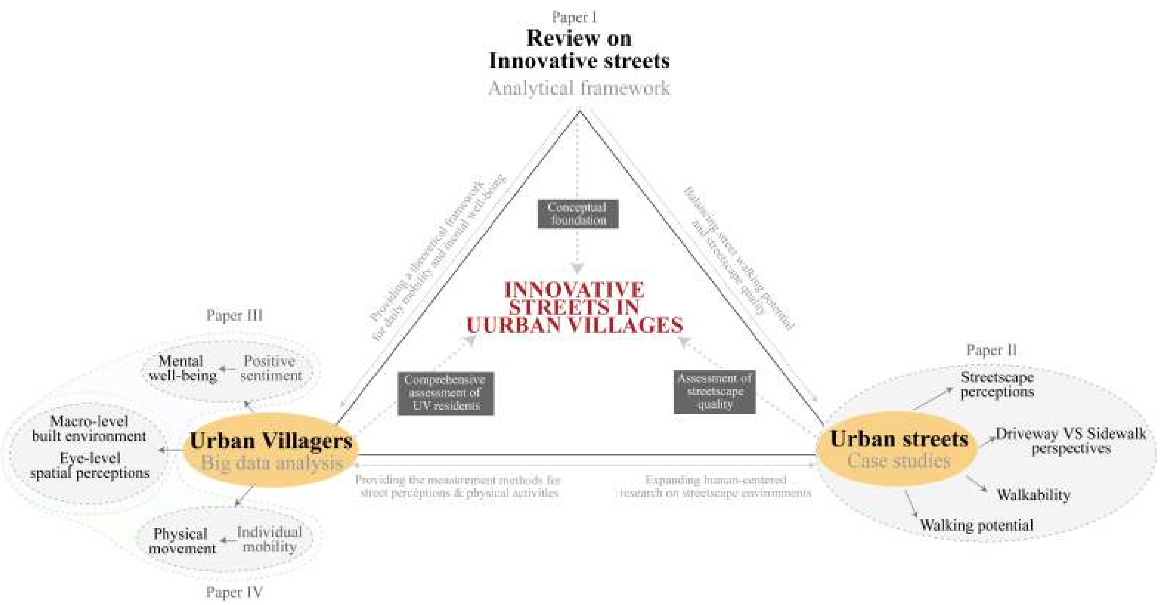


Figure 1.2: The structure of the thesis.

Figure 1.2 provides an overview of the dissertation's structure and its embedded researchprojects.

This thesis is structured as shown in Figure 1.2, aiming to systematically develop the theoretical and practical system of "Innovative Streets" in the street environments of Chinese UVs from the conceptual framework to empirical research. To better illustrate the integrity of this study on a theoretical level and the diversity of its methodology, the thesis places four independent studies (Paper I, Paper II, Paper III, Paper IV) within a unified logical framework. Each paper approaches the complex issue of "urban village streets" from different perspectives, culminating in a comprehensive summary and elevation in the final stage. The following is a more detailed explanation of the content and internal logic of each part:

First, Paper I sets the theoretical foundation for the concept of "innovative streets," exploring quantitative methods for studying the physical characteristics of streets in urban planning and incorporating residential perception studies to provide new ideas for the transformation of village streets in urban areas. Reviewing traditional urban design theories (such as image-making, street enclosure, walkability) alongside modern data analysis techniques (such as computer vision and spatial semantic analysis), Paper I proposes the multidimensional connotations of "innovative streets," emphasizing not only the accessibility and physical elements but also the psychological well-being, social interactions, and economic vitality of residents.

Subsequently, Paper II shifts the research focus to case studies of pedestrian-friendly streets in European cities like Düsseldorf, Germany, to validate the feasibility and methodological adaptability of the "innovative streets" concept in high-level urban planning. Paper II examines the balance between objective environmental indicators of streets (such as network connectivity, accessibility, walking environments) and residents' subjective perceptions of street quality, employing multi-source data like GIS and street view image analysis for empirical research. By contrasting with European cities, Paper II identifies quantifiable indicators transferable to urban village streets and adjustments needed, providing methodological references for subsequent case studies in UVs.

Paper III and Paper IV are then conducted on the ground in the urban villages of Shenzhen, focusing on the in-depth quantification of street scales and the interaction with subjective perceptions. Given the high-density construction, spatial congestion, inadequate infrastructure, and complex social relationships in urban villages, traditional single indicators are inadequate to reflect their characteristics. Paper III approaches from psychological and social perspectives, utilizing social media geolocation data to study the promoting effects of the street environment on psychological health and emotional welfare (such as a sense of spatial belonging, safety, and neighborhood interaction). Paper IV focuses on street dynamics and residents' activity characteristics, particularly walking preferences and the impact of street spaces on vitality, using drone monitoring and street view image segmentation combined with field observations to explore how micro-environmental elements (such as greenery coverage, building facades, and street facility distribution) affect residents' daily behavior patterns.

In the final synthesis section, a comprehensive reflection and re-evaluation of the "innovative streets" in the context of UVs are conducted through cross-analysis of the four research outcomes.

Chapter 2

Theoretical foundation

2.1 Definition of UVs (informal settlements in China)

In a narrow sense, UVs refer to neighborhoods that, since the reform and opening up, have been engulfed by the rapid expansion of urban land due to swift urban construction and urbanization in some economically developed areas or cities (Wong et al., 2024; Gao et al., 2020). This expansion has transformed the surrounding rural areas and their arable land into urban territories, changing the majority of these lands from being collectively owned by the working masses to state ownership (Wu et al., 2020b). However, the lands returned to the villages and the original residential lands, self-retained hills, and hillocks during the land requisition process retained their collective ownership. The neighborhoods formed on these lands primarily for residential purposes are thus known as "villages within the city." In a broader sense, UVs are defined as central villages that have been included within the overall urban development planning area, with little to no agricultural land left, and the residents have mostly transitioned away from agriculture (Wang et al., 2009).

As an emerging socio-spatial phenomenon in the rapid urbanization process of China, UVs display the complexities and contradictions at the urban-rural interface (Wong et al., 2024). These neighborhoods are usually located on the fringes of cities, and they stand in stark contrast to traditional urban residential areas across various dimensions such as geography, population, architecture, and socio-economics. UVs exhibit distinctive characteristics from regular urban residential areas in terms of land ownership, housing construction, neighborhood governance, and infrastructure development (Gao et al., 2020).

From the perspective of land use rights, the background of collective ownership in UVs leads to low efficiency and functionality of land use (Yuan et al., 2020). This not only impedes the effective development of land resources but also results in the irregularity of the land market, further affecting the optimization of the urban spatial structure (He et al., 2020). Architecturally and spatially, UVs often have high building densities but lack in structural safety, construction quality, and planning rationality (Cui et al., 2023). The prevalence of unauthorized constructions not only tarnishes the urban image but also exacerbates the imbalance in urban functions. In terms of population composition, UVs are predominantly inhabited by migrant workers, a group with relatively low socio-economic status and varying levels of education, affecting the cultural diversity and social stability of the neighborhood (Pan and Du, 2021; Liu, 2023). The diverse and transient nature of these residents' employment structures presents differences in the demographic dynamics of UVs compared to other urban areas, posing additional challenges for urban social management (Yang and van Oostrum, 2020). Regarding transportation infrastructure, the lack of planning in UVs results in chaotic internal road systems, where the management of traffic flow and parking exacerbates urban congestion (Chen and Li, 2023). This situation affects both the residents' daily commutes and the effective operation of the urban transportation system on a macro level. Economically, the rental housing-driven economic model of UVs, while providing low-cost housing options, also turns these areas into hubs for low-end services and labor markets in the city, further accentuating the economic monotony and urban-rural disparities (Zhou et al., 2022).

UVs, as an emerging phenomenon to China's rapid urbanization, exhibit differences from formal residential areas in terms of mental well-being and individual mobility (Hao et al., 2012; Yu et al., 2019; Gao et al., 2020). These differences stem from the nature of UVs, including informal living conditions and limited neighborhood resources and infrastructure. In terms of mental well-being, residents of UVs may face health challenges due to the high-density living environment, lack of neighborhood support systems, and gentrification, despite UVs offering inexpensive living spaces (Wang et al., 2019). In terms of individual mobility, the main challenges faced by residents include inadequate transportation infrastructure and limited public transportation services (van Oostrum, 2021). Although UVs are typically located near city centers, theoretically providing convenient access to work and amenities, in reality, narrow streets and mixed traffic limit the efficiency of residents' commutes, potentially affecting their ability to access urban resources and the convenience of daily life (Wu et al., 2020b).

2.2 The formation of UVs

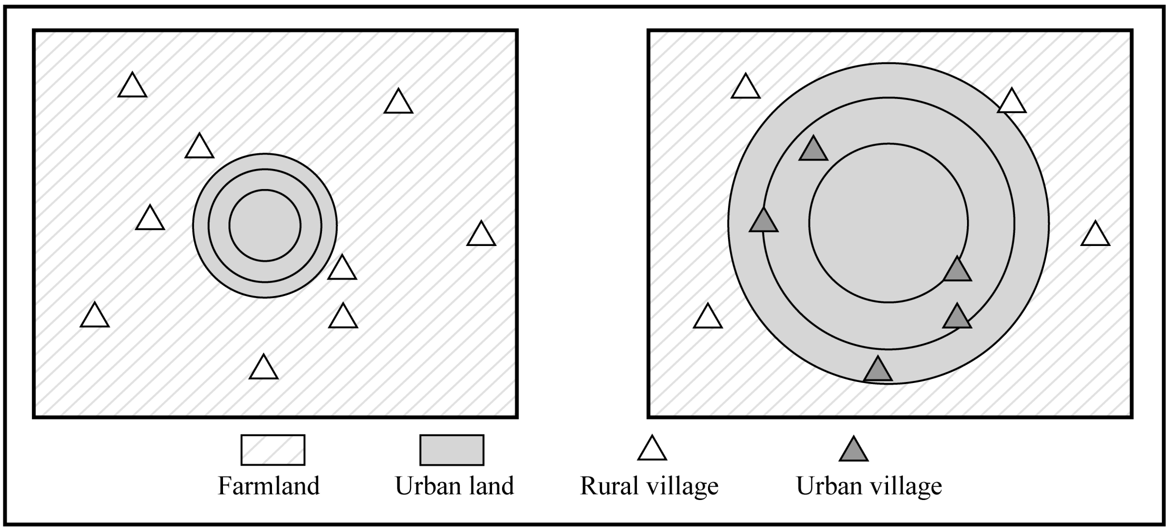


Figure 2.1: Formation of UVs.

The formation of UVs in China is a typical phenomenon of urbanization, mainly attributed to the rapid urban sprawl in urban periphery areas (Figure 2.1)(Gao et al., 2020). In the past few decades of rapid urbanization, a large number of rural areas were engulfed by the urban environment. In this process, the original rural neighborhoods were surrounded by the wave of urbanization, but villagers still retained ownership of their land and housing (Cui et al., 2023). Because urbanization outpaced urban planning and management, these areas often failed to be timely integrated into the urban planning system (Cui et al., 2023). Despite being geographically within urban boundaries, these neighborhoods still retained rural characteristics in terms of planning, construction, and management. Under these geographical and socio-economic conditions, the phenomenon of "UVs," neither typical urban areas nor traditional rural areas, emerged (Liu et al., 2010).

As the first city in China to achieve urbanization, Shenzhen's urban development trajectory offers a novel perspective for observing and analyzing UVs, a legacy issue of urbanization. The existence of UVs reflects not only the historical and social structures left over from rapid urban expansion but also the socio-economic dynamics of urbanization. As a typical immigrant city, the continuous growth of Shenzhen's external population has triggered a massive demand for housing (Pan and Du, 2021). In this context, the role of UVs becomes particularly important; they play a key role in providing affordable housing, meeting the basic residential needs of a large number of immigrants. Unlike most UVs in Chinese cities, which are mainly concentrated on the outskirts or between the center and outskirts, Shenzhen's UVs are more widely distributed and dispersed (Cui et al., 2023). This dispersed spatial distribution pattern results from Shenzhen's urban development history, where many urban constructions in the city center post-reform were built on the basis of existing UVs.

2.3 Key controversies in the transformation of UVs in Shenzhen

The transformation of UVs is fraught with controversies spanning socioeconomic equity, urban governance, and spatial planning. This section delves into the core issues of these controversies from three perspectives.

2.3.1 Socioeconomic segregation and "Gentrification"

The socioeconomic segregation and "gentrification" phenomenon in Shenzhen's UVs are the result of rapid urban development, reflecting the issues of spatial restructuring and social exclusion in the urbanization process (Mohamed et al., 2022). UVs, as unique spaces at the intersection of urban and rural areas, have spontaneously formed low-cost residential zones that provide crucial support for a large number of rural migrants (Dovey and King, 2011). However, as land values in Shenzhen continue to rise, government-led urban redevelopment projects have gradually turned UVs into hotspots for gentrification, attracting capital and the middle class, which in turn marginalizes and displaces the original residents (Berghauser Pont and Haupt, 2009).

The emergence of gentrification in UVs is not only a manifestation of socioeconomic segregation but also reveals the unequal spatial restructuring in the process of urban renewal (Pan et al., 2020). In this context, low-income groups, especially rural migrants, face the risk of forced displacement and the loss of economic and social security (Chen and Li, 2023). This phenomenon mirrors the contradictions between collective ownership and the market economy, where the weakening of social identity and the unfair distribution of benefits place low-income groups in a passive position during urbanization (Tan et al., 2019). Meanwhile, as carriers of local culture and social capital, UVs see their local values eroded and their cultural characteristics gradually replaced by market-driven commercial functions during the gentrification process (?). These changes lead to the breakdown of social relationships and the loss of community identity, severely affecting the social networks and daily lives of UV residents.

Moreover, gentrification is often oriented towards urban redevelopment and spatial upgrading, manifesting in large-scale architectural renovations and infrastructure updates (Wissink et al., 2012). However, this development model overlooks the original social structure and economic ecology of UVs, tending to simplify their function as tools for enhancing urban image and land value (Hao et al., 2012). In the process, informal housing and spontaneous economic models in UVs are dismantled, and low-cost housing resources are replaced by high-end residential and commercial real estate, making it difficult for the original socially disadvantaged groups to continue residing there (Madrazo Gonzalez, 2020). Although this urban renewal strategy promotes the improvement of urban functions and landscapes to some extent, it exacerbates spatial segregation and social exclusion within the city.

2.3.2 Informal buildings and policy conflicts

The phenomenon of informal buildings in Shenzhen's UVs reflects the misalignment between policies and the realities of urbanization, highlighting the deep-rooted contradictions between institutional frameworks and market forces. While informal buildings provide affordable housing for rural migrants and low-income groups, they also pose challenges to traditional land management systems (Dovey et al., 2015; Chen, 2022). Although these structures meet certain urban development needs, they are often regarded as disruptive to urban planning order, leading to conflicts with government-led redevelopment policies (Yang and van Oostrum, 2020).

Early urban renewal policies were primarily centered on large-scale demolitions, aiming to improve the city's appearance through redevelopment projects (Wu et al., 2013). However, these policies often overlooked the actual needs of residents in urban villages and the underlying social issues. Demolition efforts not only endangered the survival of informal structures but also compromised the housing rights of low-income groups, exacerbating social tensions (Jacobs, 1993). The implementation of such policies failed to balance economic development with social welfare. At the same time, the process of ”legalizing” informal buildings within urban renewal efforts also reveals policy instability (van Oostrum, 2020b). While some local policies tacitly allowed the existence of these buildings to a certain extent, the push for comprehensive redevelopment plans has placed dual pressures on low-income residents in terms of housing and living space. Therefore, the challenge of how to regulate informal buildings and find innovative policy solutions has become crucial in the redevelopment of UVs.

2.3.3 Adaptability and sustainability of redevelopment models

Current redevelopment plans primarily rely on collaborations between the government and private developers, using market mechanisms to achieve efficient land use (Su-Jan et al., 2012). However, this ”market-oriented” redevelopment model often overlooks the unique social structures and spatial functions of UVs, focusing excessively on the economic value of land while neglecting the long-term needs of UV residents and community resilience (Tan et al., 2019). Studies suggest that simple demolition and reconstruction do not address the deep-rooted issues of UVs and may instead disrupt their diverse land-use patterns and the survival of informal economies (He et al., 2010). Thus, finding a balance between preserving the unique social and cultural functions of UVs and achieving sustainable urban development has become one of the central controversies in redevelopment efforts.

The adaptive redevelopment model emphasizes the flexible adjustment of strategies based on the specific characteristics of each UV. In this process, fragmented land ownership and complex stakeholder interests present major obstacles (Knaap and Rey, 2023). Research indicates that village-owned industrial land with high transportation accessibility and proximity to the city center holds greater potential for sustainable development (Manganelli et al., 2020). However, a market-driven model tends to overlook the interests of residents, particularly the long-term migrant population, who play a crucial role in the urban economy (Guo and Liu, 2021). This highlights the lack of social inclusiveness in redevelopment and the marginalization issues that arise from it.

In terms of sustainability, an inclusive redevelopment model should not only focus on the renewal of physical spaces but also address the equitable distribution of social spaces (Guo et al., 2017). Incorporating socially inclusive planning strategies can sustain the economic livelihoods of migrant populations while enhancing community resilience to promote the long-term sustainable transformation of UVs (Li et al., 2021a).

2.4 Spatial patterns of UVs

The morphology of UVs is a key research area, focusing on their residential structure and developmental process (Gao et al., 2020; van Oostrum, 2020b). In the context of urban planning and urban morphology, the morphological characteristics of UVs are considered to include four core elements: built environment density, the use and encroachment of street space, functional diversity, and the interplay between residence and work, as well as street interfaces. The interaction and comprehensive analysis of these elements are crucial for understanding the structure and evolution of UVs as a special urban space (Dovey and King, 2011). This section will explore the specific definitions and measurement methods of these morphological elements in the context of UVs.

2.4.1 Built environment density

Density, as a key indicator for measuring the morphology of UVs, is associated with variables such as building height, FAR, and land coverage rate. Various studies have classified UVs based on total density or net density to reflect the building intensity at different levels within an urban area. Berghauser Pont and Haupt (2009) proposed four urban area levels to explain the application of density, which include plot, block, structure, and district levels, thereby providing a detailed perspective on the diversity of UV morphology. Pan et al. (2020) used deep learning methods, specifically the U-net architecture, to map the UVs of Guangzhou, China. Their research demonstrated the effectiveness of this approach in characterizing individual buildings in high-density environments. van Oostrum (2021) conducted extensive mapping and comparison of UVs in Beijing, Guangzhou, Delhi, and Bangalore to understand their spatial organization in terms of access networks, building density, and functional mix. Regarding built environment density, Gao et al. (2020) found that building height is not influenced by the centrality of buildings or land value; however, it is likely to be influenced by planning agreements between village committees and local governments. Niu et al. (2021) identified the building functions of UVs in Haizhu District, Guangzhou, using a three-stage model that integrates multi-source data. The study showed that building height and density play a key role in characterizing the residential buildings in UVs.

2.4.2 The use and encroachment of street space

Li et al. (2014b) explored street space and the quality of street life in Baishizhou (UV) in Shenzhen. The findings indicated that street space accessibility is weak and the comprehensive quality of the space is low. Most public activities are essential activities. People tend to expect different types of activities and functional facilities, as well as a comfortable, safe, and green environment. The study suggests establishing a slow traffic system; providing rest and landscape facilities; enhancing safety, and increasing the use of boundary spaces to address most economic and practical issues.van Oostrum (2020a) investigated the spatial encroachment of informal alleys in UVs and their impact on urban life. The study proposed a theoretical framework after a meticulous survey and analysis of over 45 kilometers of alleys in 12 different density UVs in China and India. This framework focuses on analyzing the modes of alley space occupation, including cantilevering (extension of upper space), serration (encroachment of lower space), and appropriation (claiming of space). The study pointed out that the occupation of street space is not a disorderly phenomenon but an orderly process regulated by formal norms, informal enforcement rules, and cultural norms. In 2022, Van Oostrum (2022) investigated how public spaces undergo transformations in a wide mapping of twelve UVs in China and India under the context of informal urbanization. The study focused on how densification affects the intensity and distribution of public space occupancy, introducing the concept of "public domain space". This concept elucidates that people's use of public spaces is not only passive but also includes performative rules they enact in the process of tacit monitoring and self-regulation of these spaces. The findings of the study highlighted that informal urbanization is a response to the increasing intensity of urban life.

2.4.3 Functional diversity

UVs in China exhibit functional diversity and complex living-working structures against the backdrop of rapid urbanization. Studies indicate that these UVs not only provide low-cost housing for migrant workers but also serve as sites for various social and economic activities. The land use patterns, social structures, and residents' activities in UVs show diversity and dynamic changes closely related to their urban location, developmental stage, and surrounding environment. Wissink et al. (2012) discussed the transformation of China's urban spatial structure, emphasizing the role of UVs as areas with specific cultural, functional, and economic activities within the urban spatial structure. They highlighted the importance of UVs in diverse activities such as work, leisure, shopping, and housing. Hao et al. (2012) analyzed the land use diversity of 318 UVs in Shenzhen. Their research revealed that the land use patterns of UVs are related to their position in the urban structure, development stage, and surrounding development level. These patterns show notable differences inside and outside the Shenzhen Special Economic Zone, suggesting that current uniform renovation policies for UVs may be inappropriate. Liu et al. (2010) discussed the formation and dynamics of UVs from the perspective of land use transformation and property redistribution, emphasizing the inheritance of traditional social norms and networks. The study considered UVs as transitional neighborhoods characterized by unstable land rights and a mix of urban-rural social elements.

2.4.4 The interplay between residence and work

Liu et al. (2010) discussed UVs as neighborhoods of interest for urbanizing villagers, migrants settling for low-rent housing, and self-organized grassroots units in cities, emphasizing the perspective of land use transformation and property redistribution. Zhu (2016) explored residential segregation and employment patterns of migrant workers in urbanized villages in China. The study indicated that residential segregation in UVs has a positive effect on the employment outcomes of migrant workers (including employment tendencies and wages), suggesting that spillover effects exceed spatial mismatch effects. Madrazo Gonzalez (2020) focused on four types of neighborhoods in Chinese cities and their socio-spatial transformation, including traditional, former work units, commercial, and UVs, revealing that economic and housing reforms in China have created a divided city, where traditional patterns of mixed neighborhoods have been replaced by strong segregation patterns based on citizenship and income.

2.4.5 Street interfaces

Street interfaces, as transitional spaces between private and public territories, reflect the social interactions and physical layout of UVs. Dovey et al. (2015) proposed a typology of urban interfaces, classifying the physical characteristics of building edges as accessible/inaccessible, direct/recessed, opaque/transparent, car/pedestrian-oriented, thus revealing the interplay between the social and physical environments of UVs. Gao et al. (2020) studied the street morphology of Dayuan UV in Guangzhou. The results showed that the type of streets within UVs affects accessibility, functional combinations, and urban interfaces. Regarding accessibility analysis, the number of street entrances is influenced by the analyzed street type. The interfaces of formal streets have a considerable porosity, which can promote livelihoods in neighboring areas. Based on Cuiwei ancient village in Qianshan District, Zhuhai city, Chen (2022) studied the street space inside and outside the village. Using Depthmap and SPSS software, a quantitative analysis of the complex street axis space was conducted, including analysis of synergy, spatial form and vitality, pedestrian interfaces and symbiosis, traffic flow relevance, topological depth, and street space correlation.

The classification methods and analyses in these literatures provide an in-depth understanding of the morphological diversity and complexity of UVs. However, these studies have some limitations. Firstly, there is a lack of research on the internal differences and the synergy and conflict of multifunctionality within UVs, which means that the understanding of the neighborhood dynamics and functional diversity interaction within UVs is not deep enough. Secondly, case studies of China's UVs are related to international informal settlements, and overseas experiences can also be used for the governance of UVs in China, but there is no such cross-cultural and international comparative study. This limits our understanding of the universality and specificity of UV issues on a global scale. Moreover, considerations of morphology lack meticulous observation and could actually be combined with more equipment for field research to consider space from the perspective of residents. This means that current research may overlook the actual details of residents' daily life experiences and spatial usage, which are crucial for a complete understanding and improvement of the spatial quality of UVs.

Chapter 3

The current state of the art

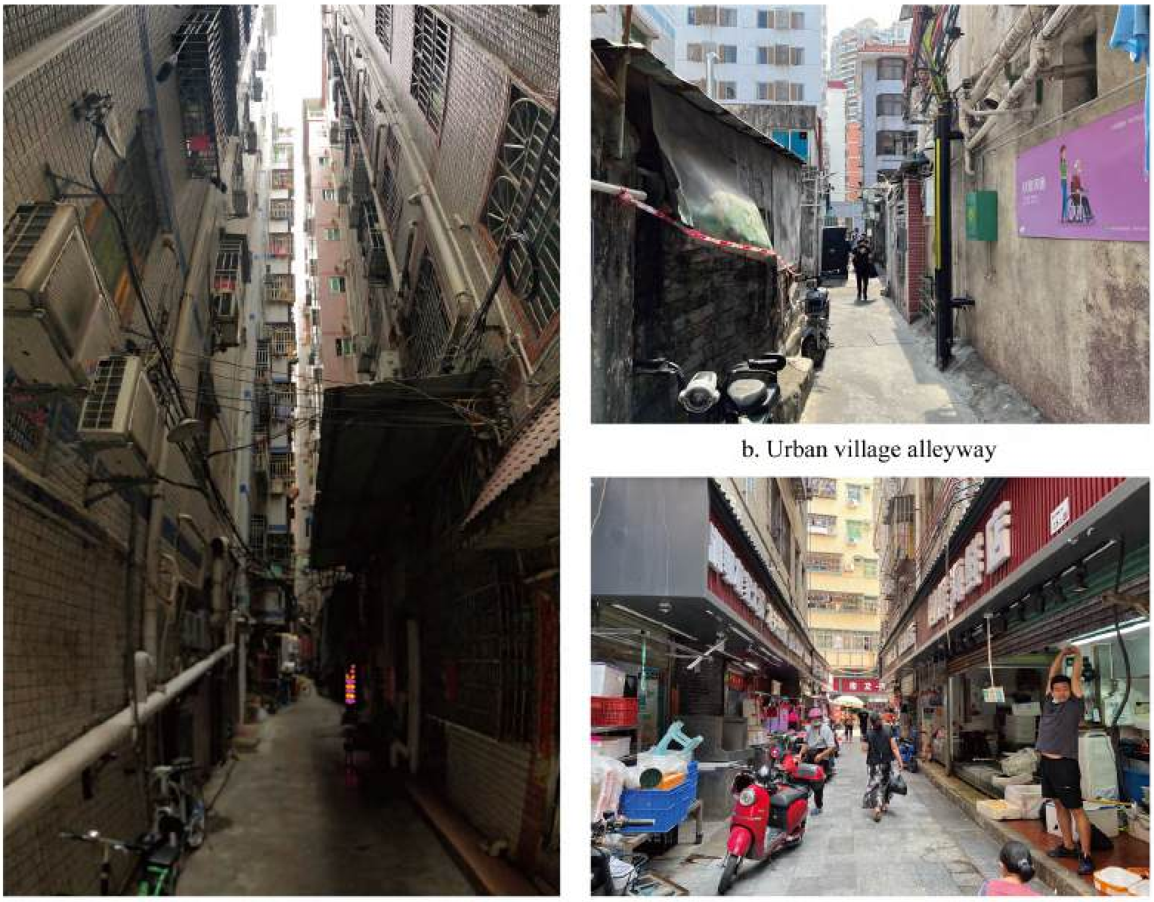
3.1 The role of UV streets in residents' daily lives

Urban streets, as pillars of city infrastructure, serve multiple functions such as transportation, recreation, social interaction, and reproduction. Advocated by Jacobs (1993), streets have increasingly become symbols of social spaces, playing everyday roles in resident communication and social harmony. UV streets play a notable role in the daily lives of residents (Figure 3.1). These areas, typically rural regions engulfed by urban expansion, have formed urban neighborhoods with special social, economic, and cultural characteristics (van Oostrum, 2020b). UV streets are not only a manifestation of physical space but also crucial sites for social interaction and cultural practices (Cui et al., 2023).

Firstly, the street spaces of UVs are the center of neighborhood life, representing a typical interface of urban-rural integration in the urbanization process (Wang et al., 2009). These streets are not only stages for the daily lives of residents but also important venues for social and cultural exchange. The narrow alleys of UVs are vibrant with life, lined with shops, snack stalls, and markets, creating a liveable urban living atmosphere (Su-Jan et al., 2012). These spaces exhibit the rapid changes of urbanization while retaining certain traditional elements of rural life, such as neighborly assistance and neighborhood cohesion. The characteristic features of UV streets are their density, diversity, and vitality. Here, different social groups—including original residents and new immigrants—intertwine in daily life, forming a complex social structure (He et al., 2010). These streets become windows showcasing socio-economic changes under urbanization, reflecting the dynamic relationship between cities and rural areas.

Secondly, the street spaces of UVs display the social and cultural dynamics of the urbanization process (Wang et al., 2009). These streets are not only places for residents' daily life and work but also representations of social relationships and power structures. Shops, restaurants, and markets on the streets serve the local neighborhood and reflect the economic activities and social interaction patterns within the neighborhood. These spaces become platforms for interaction among residents from different social classes and cultural backgrounds, thus physically and socially demonstrating the diversity and complexity of urbanization (Brindley, 2003).

Additionally, the layout and usage patterns of UV streets reveal the role of power structures in urban space (Knaap and Rey, 2023). For instance, the planning and management of streets reflect the influence of local governments and developers, while also embodying residents' control and resistance over their living spaces (Hao et al., 2011). This dynamic relationship indicates that UVs are not merely spaces passively adapting to urbanization, but places where residents actively participate in and shape their neighborhood. Social activities and interaction patterns on UV streets, such as festival celebrations, mar-



a. Shaking-hands-buildings in urban villages

b. Urban village alleyway

c. Urban village market

Figure 3.1: Different types of streets in UVs in Shenzhen.

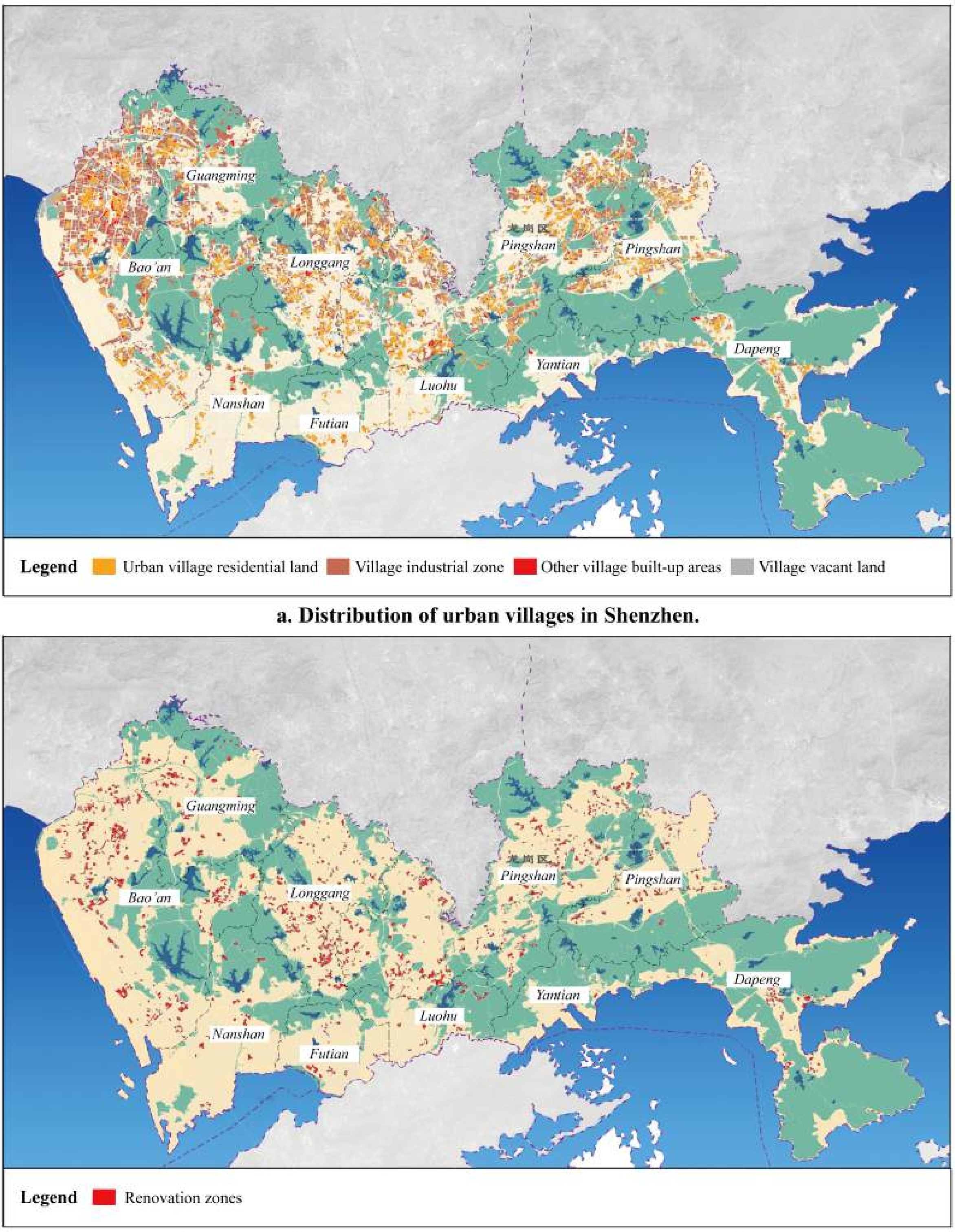
ket transactions, and neighborhood assistance, continuously reshape and reproduce the neighborhood's cultural identity and social structure (Van Oostrum, 2022). These activities not only strengthen neighborhood cohesion but also reflect the integration and conflict of social classes and cultural differences in the urbanization process (Yang and van Oostrum, 2020). Therefore, the street spaces of UVs are not just physical products of urbanization but important scenes in the evolution of urban social structures and cultural identities.

3.2 Political background of transforming UVs

UV transformation has always been a key issue in Shenzhen's urban development process. Particularly, the comprehensive renovation model emphasized in the "Shenzhen UV (Old Village) Master Plan (2018-2025)" not only signifies attention to detailed planning and comprehensive reform in urban renewal but also represents a profound reflection and innovation on traditional urban transformation methods. According to this plan, Shenzhen designated a comprehensive renovation area of 99 square kilometers (Figure 3.2), aiming to guide the gradual transformation of UVs through functional transformation and partial demolition and reconstruction. The comprehensive renovation model, compared to the traditional demolition and reconstruction model, focuses more on maximizing public interest (Manganelli et al., 2020). Under this model, the government's role is more prominent, ensuring the reasonable protection of villagers' interests while allowing enterprises to participate in the transformation with guaranteed basic profits (Guo and Liu, 2021). Post-renovation, the housing provided is rented out at a level below the market rate for similar housing, effectively reducing the housing burden for the migrant population.

The transformation of UVs, due to their extensive land coverage, numerous projects, and long implementation period, has become a focus. Since the launch of Shenzhen's first UV transformation project - Yumin Village, nearly 20 years have passed. Despite long-term exploration and practice, the renewal model of UVs still seems relatively singular, mostly involving government policy and platform support with developers carrying out actual operations. After ensuring compensation for villagers' and village collectives' interests, they are typically transformed through commercial development. However, this renewal model often overlooks the interests of a large number of tenants and may undermine the intrinsic value of UVs (Chen et al., 2023). While it may seem one-sided to generalize all urban renewal projects, the rationale behind this mainstream model deserves deep consideration. Historically, UVs have often been derogated as "urban tumors" or "urban diseases," seen as objects to be eradicated. Indeed, many UVs have left an impression of being "dirty, messy, and bad," characterized by litter everywhere, pungent odors, and ubiquitous wiring. Due to their extremely high building density, common phenomena include "handshake buildings" and "slit between the skies," which hardly meet basic living needs such as ventilation, lighting, and hygiene. Additionally, the narrow roads make it difficult for large vehicles to enter, potentially complicating rescue efforts in emergencies like fires. The phenomenon of illegal construction in UVs is severe, and the large migrant population leads to insufficient infrastructure capacity, lagging neighborhood management, and sometimes breeding criminal activities (Ma et al., 2022). However, over time, many UVs have addressed these physical and security issues to some extent through spatial transformation and management improvements.

Nevertheless, UVs carry a substantial amount of historical and cultural space information in Shenzhen. The discussion on the positive values of UVs is gradually increasing, especially for Shenzhen, where UVs have additional cultural significance and economic value (Pan and Du, 2021). On one hand, they provide affordable residential and commercial spaces, offering a foundation for survival and development for many migrant workers and small business owners (Jin et al., 2021). On the other hand, the existence of UVs also reflects social issues in urban development, such as urban-rural dual structure, land use rights, and urban planning and management (Li, 2022). As research and discussion on UVs deepen, it is recognized that UVs are not just "problem areas" in urban development but are important embodiments of urban cultural diversity and historical continuity. The perceptions of government, developers, villagers, experts, scholars, and citizens towards UVs are becoming more three-dimensional and comprehensive (Zhang et al., 2023). There is a growing interest in exploring and utilizing the positive values of UVs from different perspectives, such as preserving and enhancing their cultural characteristics in urban renewal and neighborhood development (Pan and Du, 2021), achieving a balance between urban development and historical cultural heritage (Zhou et al., 2022). Therefore, UVs are no longer seen merely as obstacles to urban development but as a special urban spatial form and cultural carrier, re-evaluated and imbued with new meanings. Through rational planning and development of UVs, they can be better integrated into the overall urban development while preserving and passing on the city's historical and cultural heritage.



b. Comprehensive renovation zoning map of urban villages in Shenzhen.

Figure 3.2: Distribution of UVs and comprehensive renovation zoning map.

3.3 Innovative streets and urban mobility

Existing research has made significant progress in the areas of intelligent transportation systems and technological innovations. Many studies focused on innovations such as intelligent transportation systems, alternative fuel systems, autonomous driving systems, shared mobility services, demand-responsive transport, and comprehensive transportation systems. These technologies aim to reduce traffic congestion, energy consumption, and environmental pollution, and to improve road safety and transportation efficiency. For example, Butler et al. (2020) categorized and evaluated these technologies, discussing their impact on traffic safety, road congestion, energy consumption, the environment, and accessibility.

In terms of the multifunctionality of streets, research has emphasized that streets are not only conduits for traffic but also vital public spaces. Studies highlight the significance of integrating smart street facilities with the IoT, adopting mixed patterns of grid and radial street networks, and creating safe street environments for enhancing urban mobility. Pedestrian and bicycle-friendly street environments can enhance social interaction and urban livability. Research by Rui and Othengrafen (2023) demonstrates that combining these measures can enhance urban mobility efficiency and livability. Furthermore, to adapt to the rapid development of shared mobility, some studies have proposed innovative urban planning models. These models aim to create shared infrastructure and provide quantitative analysis of short-term and long-term innovative transportation strategies, helping urban planners assess the potential impact and benefits of different strategies (Butler et al., 2020; Cervero et al., 2017). The model proposed by Karim (2017) is an example, assisting municipal authorities and system planners in accurately quantifying the scale and costs of various innovative transportation strategies.

In the context of human-centered smart city concepts, studies have explored the integration of urban technology with the citizen experience. Research advocates viewing streets as multifunctional spaces and promotes a design-driven approach to achieve symbiosis between urban settings and technology. Research by Andreani, Andreani et al. (2019) explored the development pathways of adaptive street environments, responsive urban safety, and dynamic retail spaces in medium-sized European cities through design research models.

Despite advancements in multiple areas, some contradictions and conflicts remain. First is the contradiction between technology-first and people-first approaches. Some studies emphasize technology-driven solutions, such as autonomous driving and intelligent transportation systems, while others highlight people-driven design and planning approaches. Sevtsuk and Davis (2019) argue that while technology can provide personalized and cost-effective urban mobility solutions, prioritizing the interests of pedestrians, cyclists, and public transit users is essential to avoid worsening traffic congestion and urban sprawl. Alberti (2023) further emphasizes the importance of reconceptualizing streets as multifunctional spaces. Another major contradiction is the challenge of policy and implementation. Although many studies propose advanced technological solutions, the complexity of policy and planning often becomes a major obstacle in practice. Trombin et al. (2020) noted that the successful implementation of smart cities requires strong policy support and cross-sector collaboration. Nicolaï and Nicolaï and Le Boennec (2018) also stressed the important role of public policy in managing these changes.

Current research also exhibits some shortcomings. First, there is a lack of an integrated perspective. Most studies explore from a single angle, lacking a comprehensive framework for assessing the multifaceted impacts of innovative streets and urban mobility. Second, there is a deficiency in empirical research. Although studies propose theoretical frameworks and models, there is a lack of large-scale empirical research to verify the practical effects of these theories and models. Finally, there is a lack of a global perspective. Most studies focus on specific regions or cities, lacking comparative analysis of urban mobility innovations under different geographic and economic backgrounds. Medina-Molina et al. (2022) highlighted that the applicability of different cities' transportation innovation experiences on a global scale still requires further study.

3.4 Innovative streets and residents' mental well-being

Besides the positive contributions of innovative streets to urban mobility, their impact on mental well-being has become an increasingly important area of research. As urbanization accelerates and the influence of the urban environment on residents' mental well-being becomes more evident, researchers are focusing on how innovative street design can enhance the mental well-being of urban residents.

Innovative street design is considered a vital means to promote urban sustainability. Street greening is an important factor in enhancing residents' mental well-being. Studies have found that streets with a high degree of greening can reduce stress levels, improve air quality, reduce noise, and enhance social cohesion, all of which positively impact mental well-being. Research by Wang et al. (2019) indicates that both streetscape greening and remote-sensed greening, measured by two different methods, are positively correlated with mental well-being. Physical activity, stress, air quality, noise, and social cohesion are some of the mediating factors. However, over-reliance on greening to enhance mental well-being may overlook the importance of other environmental and social factors and could lead to unequal resource distribution. Higher-income neighborhoods might more easily receive enhancements in greening and public spaces, whereas lower-income neighborhoods might be neglected.

Secondly, "Play Streets" provide safe activity spaces through the temporary activation of public spaces, promoting not only physical activity but also enhancing neighborhood social support and cohesion, which positively impacts mental well-being. Research by Umstattd Meyer et al. (2021) demonstrates that this strategy not only promotes physical activity but also enhances neighborhood social support and cohesion, positively affecting the mental well-being and overall health of the neighborhood. However, the issue of uneven resource distribution associated with temporary public spaces needs to be taken seriously.

Additionally, smart city technologies that leverage big data and machine learning algorithms to provide personalized feedback can help change behaviors to improve mental well-being. These technological means enhance residents' understanding of their behaviors and environments, thus promoting mental well-being. Research by Sas et al. (2020) shows that personalized feedback provided by big data and machine learning algorithms can improve residents' mental well-being. However, this could also lead to increased reliance on technology and data privacy issues, whose long-term impacts on mental well-being are still unclear.

Although IoT technology and big data analysis have shown great potential in enhancing street innovation and mental well-being, over-reliance on these technologies may lead to privacy and data security issues. These concerns could cause unease and stress among residents, potentially offsetting the positive effects brought by the technology. Current research indicates a contradiction between technology and privacy, requiring further studies to balance these aspects (Rui and Othengrafen, 2023). Also, the design of street greening and temporary public spaces often suffers from unequal resource distribution, which can lead to social inequity. For instance, higher-income neighborhoods might more easily receive enhancements in greening and public spaces, while lower-income neighborhoods might be overlooked (Lo and Jim, 2010). This unequal resource distribution might exacerbate inequalities in mental well-being.

Current research demonstrates the role of innovative street design in enhancing urban residents' mental well-being. However, contradictions such as technology versus privacy, environmental design versus social equity, and short-term effects versus long-term impacts need further exploration. Many studies focus on the short-term positive impacts of innovative street design on mental well-being, but there is less research on long-term impacts. The long-term effects of temporary public spaces and smart city technologies have not been fully validated, requiring more longitudinal studies to assess their long-term effects. Although existing cross-sectional studies provide some short-term data, the lack of in-depth exploration of long-term effects is a research gap that needs further filling (Umstattd Meyer et al., 2021). Current research on innovative streets and mental well-being is predominantly cross-sectional, lacking longitudinal studies to assess long-term impacts. Current studies focus primarily on overall effects, lacking an in-depth exploration of the differential impacts under different socio-economic backgrounds (Lo and Jim, 2010). Smart city technology has shown great potential in enhancing mental well-being, but its ethical issues have not been fully discussed. The rapid development of technology, while bringing many conveniences, also poses potential ethical problems and threats to residents' privacy, which need to be addressed in future research and applications (Sas et al., 2020).

3.5 Assessment of neighborhood streets in UVs

UV streets are not only conduits connecting different places but also vital spaces for social interaction, commercial activities, and cultural exchanges among residents (Sucher, 2010). As urbanization progresses, these street spaces have become an indispensable part of urban structure and social organization. Therefore, accurate and comprehensive assessment of UV street spaces is crucial for understanding and improving the living environment of residents.

Firstly, the assessment methods of UV street spaces can be divided into two main categories: subjective and objective assessment. In terms of subjective assessment, questionnaires are one of the commonly used methods. Through questionnaires, researchers can obtain residents' views and feelings about street spaces, and these data are important for guiding the design and transformation of street spaces. For example, Cui et al. (2023) explored the nocturnal space characteristics and pedestrian needs in UVs through literature reviews, field investigations, and semi-structured interviews. They also employed a combination of the Kano model and the Analytic Hierarchy Process (AHP), with the aim of constructing a pedestrian needs-based assessment system. By conducting questionnaire surveys with pedestrians on the main streets of Pingshan Village and Nantou Ancient City in Shenzhen, the study revealed the dominant categories of nighttime pedestrian needs and satisfaction assessments for these UV street spaces. Similarly, Shen et al. (2023) used photo elicitation to survey physical factors such as building facades, plant landscapes, roads, and municipal public facilities diversity in four UV reconstruction projects in Guangdong Province. The survey included UV residents with different demographic characteristics. The study found that refurbished and decorated building facades, diversified plant species, repaved roads, and moderately diversified municipal public facilities were favored by residents. Residents with different demographic characteristics also had different visual preference assessments for different physical factors in the reconstructed UVs. Additionally, Kumar (2020) focused on UVs in Delhi and conducted an in-depth analysis of existing evaluation methods. The study reviewed the theoretical foundations of architectural environment quality assessment and developed an assessment framework adapted to local and similar areas. This framework was built on the basis of an UV quality assessment model, with a particular emphasis on material considerations and a thorough examination of the environmental and social conditions of UVs. Practical testing in two rapidly developing but infrastructurally backward UVs in Delhi revealed that the assessment framework effectively identified key factors leading to the decline in urban quality of UVs.

In the field of objective assessment of urban street space quality, spatial data technology has become an indispensable tool. By utilizing GIS and remote sensing technologies, researchers can analyze the road network structure and spatial distribution of streets in-depth, thus assessing the characteristics of streets from a macro perspective. For example, Tiarasari and Kartidjo (2021) employed the method of urban network analysis in their research. This method uses five network centrality indicators in spatial networks, including Reach, Gravity Index, Betweenness, Closeness, and Straightness, to quantify the impact of environmental design on urban spaces. As part of the ArcGIS toolbox, urban network analysis can effectively assess how environmental design influences spatial accessibility and pedestrian flow in urban areas. On the other hand, Najmi (2021) combined Remote Sensing Images with SVIs for more precise mapping of UV areas. Implemented in the Kampung areas of Jakarta, the study fine-tuned the Places365-VGG16 network and used SVI to extract highly detailed spatial features. These features were then combined with RSI data and analyzed using the FCN-DK6-i and Modified FCN-DK6 networks for the location and mapping of slums. This method effectively combined two types of image data, demonstrating efficiency in understanding and identifying urban poverty areas.

In the fields of urban planning and environmental assessment, the trend of using SVI and CV technologies as analytical tools is on the rise (Niu et al., 2021; Qiu et al., 2021; Long and Huang, 2019; Tang and Long, 2019). SVI offers an advantage over traditional aerial photography or satellite images by providing a human perspective view of the urban built environment, making it an essential tool for understanding urban spatial quality.

Li et al. (2015) used Google SVIs combined with a modified Green View Index to assess the greenness of urban streets. They applied advanced deep learning and semantic segmentation techniques to process images, effectively extracting vegetation information from SVI and quantifying the Green View Index. This method offers a new perspective for the visualization and assessment of urban street greening. At the same time, Chen and Biljecki (2023) introduced an innovative method that combines SVI and CV with traditional geospatial and remote sensing data to automatically assess public spaces in residential areas. Their study showed that this perceptual model achieved a high degree of accuracy and reflected multiple aspects of public spaces more comprehensively than previous methods. This research demonstrated the potential of SVI in spatial assessment, expanding its research scope, and providing new ideas for the design and allocation of public spaces in urban planning. Huang et al. (2022) designed Sensing Blender, an end-to-end deep learning model that integrates remote sensing, SVI, and social perception to comprehensively characterize urban spaces. The model merged the physical characteristics of satellite and SVIs with the dynamic features of taxi trajectory data. The performance of the model was validated in the identification experiments of UVs in Shenzhen, China, providing an effective and efficient monitoring tool for urban management, decision-making, and studies on urban expansion and renewal. Moreover, Kang et al. (2023) focused their research on Jeonju, South Korea. By scraping SVIs and building a training dataset, they developed a convolutional neural network model combining Siamese networks and RankNet to predict perceived walkability scores for all collected SVIs. In terms of physical walkability assessment, based on a review of existing studies, eight indicators were selected: congestion, sidewalk fencing, sidewalk proportion, slope, greening, sky openness, POI accessibility, and distance to bus stops. Then, using semantic segmentation models, the availability of data acquisition, and the correlation between indicators, the overall physical walkability score was calculated comprehensively.

However, a critical analysis of existing research reveals several shortcomings. Firstly, SVIs are often concentrated on main roads and commercial areas of cities, while more remote or undeveloped areas may lack sufficient image coverage (Hou et al., 2024). Moreover, the frequency of updates for these images may not be sufficient to reflect the rapidly changing urban environment, such as the completion of new buildings or the progress of urban redevelopment projects. This means that analyses using SVI may be based on outdated or incomplete data. Secondly, most studies focus on the physical characteristics of street spaces and do not comprehensively reflect residents' attitudes towards UV spaces, overlooking residents' subjective experiences and socio-cultural backgrounds (Van Oostrum, 2022; Xu et al., 2024; Li et al., 2014b). These experiences affect their life satisfaction and sense of neighborhood belonging. Lastly, research on UVs lacks consideration of socio-cultural backgrounds (Qtaishat et al., 2020). UVs not only have physical characteristics but also carry rich socio-cultural backgrounds. SVI and CV methods often fail to capture these socio-cultural elements in the analysis of urban spaces, such as interactions among residents, local features, and historical traditions. The socio-cultural background of UVs has a profound impact on residents' identity recognition and neighborhood dynamics.

Chapter 4

Study area and research methods

4.1 Study area

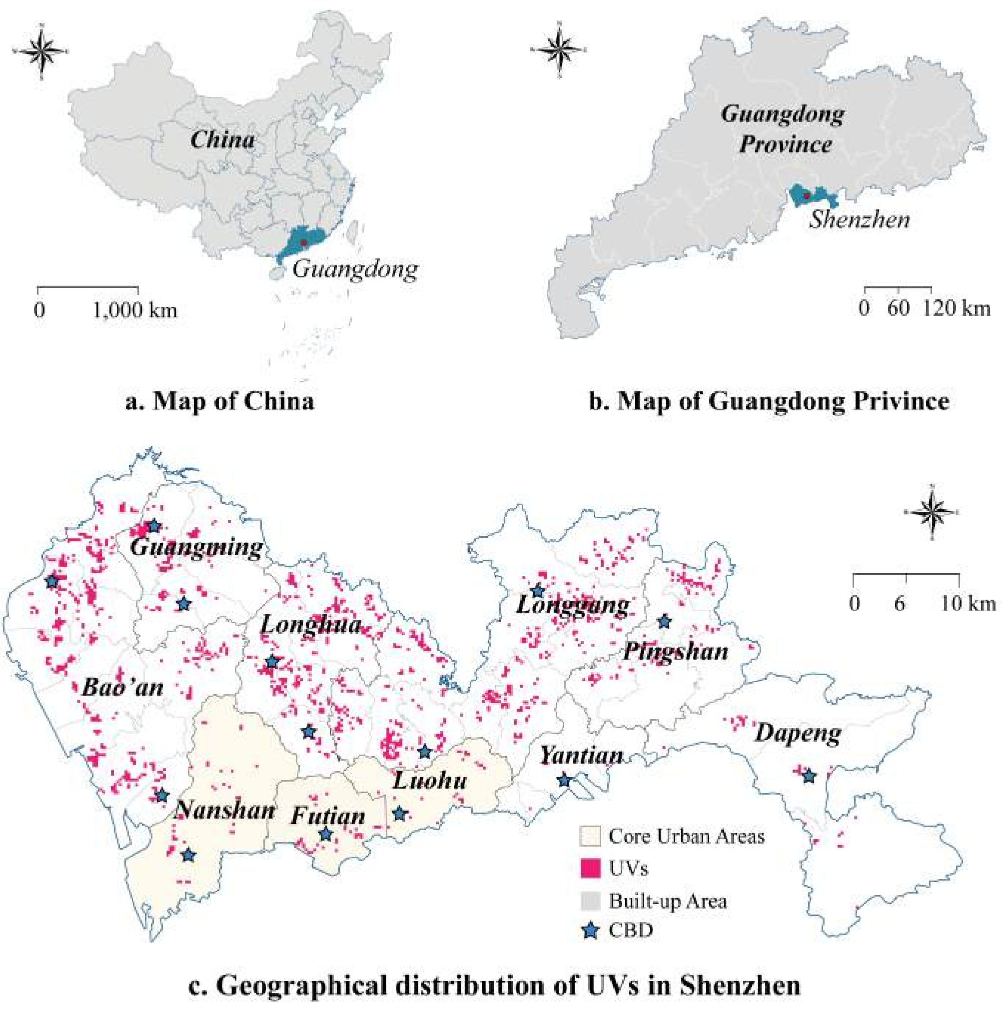


Figure 4.1: Location of Shenzhen and distribution of UVs.

This study focuses on Shenzhen as the main research area (Figure 4.1), a city that stands out due to its unique urbanization trajectory. Shenzhen can be divided into three regions: the core area (Nanshan, Futian, Luohu), the suburban area (Bao'an, Longhua, Yantian, Longgang), and the outer suburban area (Guangming, Pingshan, Dapeng). Established as one of China's first special economic zones during the Reform and Opening-up period in 1978, Shenzhen has evolved into an exemplary modern metropolis in China. However, unlike the classic prototype of an "instant city," Shenzhen's origins are closely tied to its former rural enclaves, now known as UVs (Hao et al., 2012; Wang et al., 2009).

Shenzhen hosts 1,877 UVs with an estimated population of around 12 million, primarily consisting of a migrant population (Cui et al., 2023). Due to the inadequacy of government-subsidized low-rent housing, these low-cost UVs have become the primary source of affordable housing for migrants. Currently, it is estimated that about 11 million migrants reside in these UVs (Pan and Du, 2021). This study focuses on the UVs in Shenzhen. We created a hexagonal research unit with a side length of 100 meters in ArcGIS, defining the unit as UV when the area of UV buildings exceeds that of FSs. The AOI data of UVs and the building data from OSM were obtained in January 2023. Figure 4.1 illustrates the spatial distribution of UVs, marked in blue, comprising 9,704 units (35.1%), while FS are marked in pink, comprising 17,942 units (64.9%). In 2019, the Shenzhen Municipal Planning and Natural Resources Bureau issued the "Shenzhen UV Comprehensive Renovation Action Plan (2019-2025)" to revitalize UVs through integrated facility upgrades and functional transformations.

In addition, we selected Düsseldorf as a study site to learn from its successful street design cases (Figure 4.2). Düsseldorf covers an area of 217.41 square kilometers and has a population of approximately 570,000 (Krämer et al., 2000). In the 2019 Mercer Quality of Living Survey, Düsseldorf was ranked as the sixth most livable city in Europe. For our research, we focused on roads with a speed limit below 50 km/h, as roads with speeds exceeding this limit lack sidewalks and fall outside the scope of measurement. Subsequently, we conducted a walkability potential analysis for the entire city. We chose the Old Town (Altstadt, 0.5 square kilometers), Carlstadt (0.46 square kilometers), and the City Center (Stadtmitte, 1.72 square kilometers) in District 1 as field study locations. The data for the area divisions were downloaded from the official website (https://www.duesseldorf.de/geoportal.html).

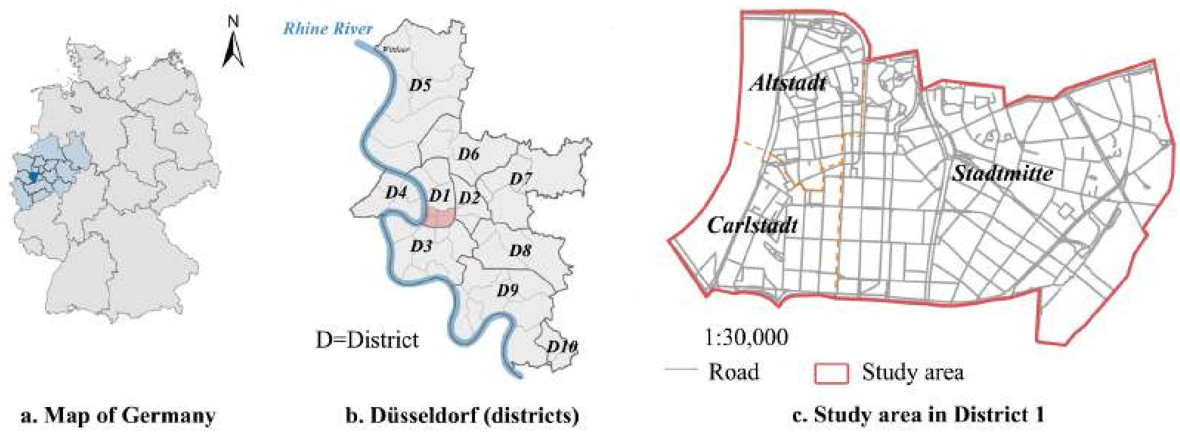


Figure 4.2: Location of Düsseldorf as the second study area.

4.2 Qualitative methods

This study employs a comprehensive approach incorporating both qualitative and quantitative research methods to analyze the relationship between innovative streets and sustainable urban transformation. In the qualitative research segment, we conducted a systematic review of relevant literature published in the Web of Science and Scopus databases between January 2000 and May 2021. Through keyword searches and rigorous classification screening, we ultimately selected 24 highly relevant articles for in-depth analysis. In the quantitative research segment, we utilized various open data sources, including Baidu Heat Map, Weibo check-in data, POI data, NDVI data, urban management and building footprint data, SVIs, and global population distribution data. By applying advanced deep learning models such as DeepLab V3+ for semantic segmentation, YOLO v7 for pedestrian tracking, and the BERT model for sentiment analysis, we conducted a detailed quantitative analysis of urban environmental features. We also explored the impact of street design on residents' social interaction and mobility.

To conduct a comprehensive and integrative literature review on the concept of innovative streets, a wide range of relevant sources were examined to find meta-analyses of published scientific papers. The review focused on articles published in the Web of Science and Scopus databases. The selected articles were published between January 2000 and May 2021, and all were in English. Due to the lack of a clear definition for the concept of innovative streets, the scope of this review was limited to urban streets that have a notable impact on social interaction and neighborhood cohesion, allowing for data extraction in a comparable context. As a first step, terms and keywords related to the concept of innovative streets were searched, including synonyms such as "neighborhood streets", "innovative streets", "walkable streets", "livable streets", "sustainable streets", "quiet streets", or "creative streets". The search was not limited to "streets", so synonyms like "avenues", "boulevards", and "roads" were also included. However, synonyms weakly related to streets, such as "street crime" or "street sewage treatment", were excluded due to their deviation from the theme. The second step linked the concept of innovative streets to urban planning and sustainability. Here, different concepts were combined with "sustainable urban transformation" or "sustainable urban planning" to identify the association between innovative streets and sustainable urban transformation; a total of 444 articles met the set criteria.

The process of data extraction involved two progressive steps. First, all article abstracts were reviewed to determine their contribution to the research topic. Specific categorization was used to select the most relevant articles:

High-level: Articles whose keywords, related terms/concepts, and conclusions were highly relevant to streets and sustainable urban transformation. For example, a longitudinal study of a Boston neighborhood commercial street confirmed the relationship between street physical design, resident behavior, and urban livability. These publications played a pivotal role in the development of innovative streets.

Mid-level: Terms and concepts overlapped with this review but were sufficient, such as case studies. Articles that examined design features for traffic or environmental purposes but did not consider street design as a means to enhance urban sustainability were considered to have medium relevance and were thus omitted.

Low-level: Topics with less relevance to this review. Some papers focused on discussing urban poverty and sewage management, where streets played a minor role in the research. These articles were excluded.

Finally, 24 articles were selected for analysis, covering innovative street approaches and sustainable urban transformation.

4.3 Quantitative methods

4.3.1 Selected variables in all Publications

In our research, we utilized open data sources across all publications, including Weibo text data, POI, as well as street and building footprint data. The definitions and calculation formulas for all variables are presented in Table 4.1, while the data sources are detailed in Table 4.2.

Table 4.1: Data and sources.

Data	Sources
Baidu heat map	Baidu (https://lbsyun.baidu.com/)
Weibo check-in	Sina Weibo (https://m.weibo.cn/)
POI data	Baidu Map (https://lbsyun.baidu.com/)
NDVI	NASA's Earth Observing System Data and Information System Reverb (http://reverb.echo.nasa.gov/)
Urban administration, street and building footprint	OpenStreetMap (https://www.openstreetmap.org)
SVI	Baidu map (https://lbsyun.baidu.com/)
Population data	WorldPop (https://www.worldpop.org/)

Baidu Heat Map data leverages the big data analytics capabilities of Baidu Maps. It is generated by aggregating user location information within specific areas, visualized through varying colors to represent the intensity of user activities in different regions. This effectively reveals the concentration and dynamic changes in population distribution.

The Weibo check-in data originates from the Sina Weibo platform, documenting geolocational information shared by users on this social media platform. Each check-in entry typically includes attributes such as user ID, check-in location, and time of check-in.

POI data, acquired through Baidu Map services, pertains to a series of geographic coordinates in the Geographic Information System, each representing specific landmarks like shops, schools, or hospitals. POI data usually includes the name of the location, category, latitude and longitude coordinates, and other potential descriptive details, forming the foundational data for geospatial analysis and location services. The classification standards for POIs are displayed in Table 4.3.

NDVI, or Normalized Difference Vegetation Index, is calculated using satellite remote sensing data provided by NASA's Earth Observing System Data and Information System, Reverb. It is an index derived by measuring the ratio of red to near-infrared light reflected by vegetation, typically ranging between -1 and 1.

Urban management, street, and building outline data are sourced from OpenStreetMap, an open-source global map database project. This data includes detailed information on administrative boundaries, street networks, building outlines, and various geographical markers. It has been instrumental for the positioning information of UVs in this study. It is important to note that, building on OSM data, we further acquired specific information about UVs from the Shenzhen Open Data Platform (https://opendata.sz.gov.cn/), which includes details about the location and size of UVs over different years.

SVIs are provided by Baidu Maps, captured through field photography on streets, showcasing the actual appearance of the urban environment. These images typically exist in a 360-degree panoramic

Table 4.2: Description of the variables and calculation of the formula.

Domains	Variables	Definition and formula
Street network	Street density	Street length / grid area (km / km2)
	Walk accessibility	
	Automobile accessibility	For the accessibility of walking and driving/automobile, we selected the Gaussian 2SFCA method for calculation. First, for each $Settlement_j$, we define the area of settlement as the service catchment S_j. Second, search all population location points within a search radius d_0 and count the total service population P_k. Third, for P_k of each $Settlement_j$, weighted by the distance decay function $G(d_{kj}, d_0)$. Finally, calculate the ratio between S_j and P_k as the walk supply-demand ratio for each settlement. The formula is shown as follows (Eq. 4.1): $$R_j = \frac{S_j}{\sum_{k \in \left\{d_{kj} \leq C_j\right\}} G\left(d_{kj}, d_0\right) P_k} \quad (4.1)$$ Where R_j is the supply-demand ratio of settlement location j. S_j is the area of settlement. P_k is the total service population in the search radius d_0. According to (Wang et al., 2013), we select 1,2 km and 7,6 km as the reasonable walking and driving distance d_0. (d_{kj}, d_0) is the Gaussian function, and d_{kj} is the walking distance between location j and population location k. The formula of the Gaussian function is shown below (Eq. 4.2): $$G\left(d_{kj}, d_0\right) = \begin{cases} \frac{e^{-\frac{1}{2} \times \left(\frac{d_{kj}}{d_0}\right)^2_{-e^{-\frac{1}{2}}}}, d_{kj} \leq d_0}{1 - e^{-\frac{1}{2}}} 0, d_{kj} > d_0 \end{cases} \quad (4.2)$$ For each location i, given a spatial distance d_0, and the supply-demand ratio R_l of the supply location l falling within the scope is weighted using a Gaussian equation. The weighted ratios are then summed to obtain the spatial accessibility A_i^F of demand location i (Eq. 4.3): $$A_i^F = \sum G\left(d_{kj}, d_0\right) R_l \quad (4.3)$$

TOD	Bus route density	Bus line meters / grid area (km / km2)
	Bus station density	Kernel density of bus stations / grid (index)
	Metro route density	Metro line meters / grid area (km / km2)
	Metro station density	Kernel density of bus stations / grid (index)
Land use intensity	Building Coverage Ratio (BCR)	The ratio of the total standing area of all buildings to the total area of the grid (Eq. 4.4): $$BCR = B/A \quad (4.4)$$ Where B and A denote the gross building footprint (km2) and gross area (km2).
	FAR(FAR)	The ratio of the gross floor area of all buildings to the total area of the grid (Eq. 4.5): $$FAR = F/A \quad (4.5)$$ Where F and A denote the grass floor area (km2) and gross area (km2).
	Land use mix (LUM)	The degree to which those different types of land uses are physically and functionally integrated (Eq. 4.6): $$LUM = -\sum (P_i)(\log P_i) \quad (4.6)$$ Where P_i the ratio of the ith land type to the total area.
Land use type	Residential density	Number of residential POIs / grid area (counts / km2).
	Commercial density	Number of commercial POIs / grid area (counts / km2).
	Industrial density	Number of industrial POIs / grid area (counts / km2).
	Public service density	Number of public service POIs / grid area (counts / km2).
	Green space density	Number of green space POIs / grid area (counts / km2).
	Transportation service density	Number of transportation facilities POIs / grid area (counts / km2).
	NDVI	Normalized Difference Vegetation Index / grid area
Streetscape perception	Greenness	Urban green spaces, such as forests, green belts and lawns, have positive implications for the design of urban landscapes (Eq. 4.7): $$G_i = \frac{1}{n}\sum_{i=1}^{n} T_n \quad (4.7)$$

Streetscape perception	Enclosure	Enclosure refers to how the built environment envelops pedestrians and is closely linked to people's perception of the livability of a place (Eq. 4.8): $$E_i = \frac{\frac{1}{n}\sum_{i=1}^{n} B_n + \frac{1}{n}\sum_{i=1}^{n} T_n}{\frac{1}{n}\sum_{i=1}^{n} R_n + \frac{1}{n}\sum_{i=1}^{n} P1_n + \frac{1}{n}\sum_{i=1}^{n} F_n} \quad (4.8)$$
	Walkability	Walkability reflects the overall level of support provided by the outdoor environment for walking (Eq. 4.9): $$W_i = \frac{\frac{1}{n}\sum_{i=1}^{n} P1_n + \frac{1}{n}\sum_{i=1}^{n} F_n}{\frac{1}{n}\sum_{i=1}^{n} R_n} \quad (4.9)$$
	Imageability	Imageability is a defining characteristic of a place that endows it with distinctiveness, recognizability, and memorability (Eq. 4.10): $$I_i = \frac{1}{n}\sum_{i=1}^{n} B_n + \frac{1}{n}\sum_{i=1}^{n} S1_n + \frac{1}{n}\sum_{i=1}^{n} P2_n \quad (4.10)$$

* T_n denotes the tree pixels; S_n denotes the sky pixels; B_n denotes the building pixels;

* R_n denotes the road pixels; $P1_n$ denotes the pavement pixels; F_n denotes the fence pixels;

* $S1_n$ denotes the sign symbol pixels; $P2_n$ denotes the person pixels.

Table 4.3: POI classification based on the Baidu platform.

Integration Clusters	**Counts**	**POI classifications**	**Secondary classifications**
Residence	30,499	Accommodation services	Neighborhoods, apartments, villa, dormitories etc.
Commerce	133,954	Business, commercial, entertainment, and other facilities	Shopping centers, restaurants, hotels, cinemas, banks etc.
Industry	90,755	Factories and industrial buildings	Companies, factories, science and technology parks, industrial parks, etc.
Public services	66,218	Land for cultural, educational, medical treatment and health, social welfare activities.	Education and culture services, health care services, sport and leisure services, government agencies, public facilities, etc.
Green space	2,637	Public places such as parks, green space, and squares.	Scenic spots, zoos, botanical gardens, parks, squares, etc.

Transportation services	47,081	All the roads, facilities, and junctions.	Parking lots, transport facility services, car and motorcycle services or repairs, etc. (Bus stations, metro stations and street intersections are excluded.)

format, offering an immersive street-level view. In this study, they are utilized to quantify residents' perceptual experiences of UVs and street spaces.

Population data is supplied by the WorldPop project, offering global population distribution estimates based on spatial analysis techniques. These data sets typically include total population numbers, population density (number of people per square kilometer), age structure, and other detailed demographic statistics.

4.3.2 Crawling of SVI in Publication II, III

This study utilizes SVI data, deeply integrated from Baidu Street View service. The primary reason for selecting Baidu Street View is its extensive coverage in Mainland China. Compared to crowdsourced image services such as Mapillary and KartaView, Baidu Street View offers higher quality and more uniform format images (Hou and Biljecki, 2022). Additionally, Baidu Street View has more comprehensive coverage in Mainland China compared to other commercial services like Google Street View (Kang et al., 2020; Wang et al., 2020).

In Figure 8, we deployed sampling points approximately every 50 meters along major and minor road networks in Shenzhen via Baidu Street View service, aiming to collect SVI more intensively for a more detailed depiction of urban environmental features (Li et al., 2018). Unlike the commonly used 100-meter interval in previous studies (e.g., Li et al., 2018; Wang et al., 2020), this study adopts a denser sampling interval, reflecting a focus on micro-scale urban environmental changes and a pursuit of detail (Kim et al., 2021). In total, over 76,839 sampling points were established.

We employed uniform camera settings and image resolution to ensure consistent perspectives, including a 120° horizontal field of view and a fixed 0° camera angle ("pitch") for capturing both upward and downward views. At each sampling point, images were captured at 0°, 90°, 180°, and 270° angles, then stitched together using OpenCV to create panoramic photos (Kang et al., 2023). Compared to traditional single or limited-angle SVI, panoramic cameras provide a more comprehensive and three-dimensional streetscape, aiding in more accurate assessment and analysis of urban spaces (Chen et al., 2020; Yin and Wang, 2016).

4.3.3 Semantic Segmentation in Publication II, III, IV

This research employs a semantic segmentation model to extract street features in a four-step process (Figure 4.4). First, the input data consists of SVI from Baidu Street View service, capturing panoramic views of the urban environment. Second, these SVIs are fed into a pre-trained deep learning model based on the DeepLab V3+ architecture for image semantic segmentation. DeepLab V3+ is an advanced deep learning architecture designed specifically for the task of image semantic segmentation and is a deep convolutional neural network model under the Atrous Spatial Pyramid Pooling module (Chen et al., 2017). Building upon its predecessors, DeepLab V1 and DeepLab V2, DeepLab V3+ further enhances the model's ability to capture spatial information of images, especially in recognizing the edges of ob-

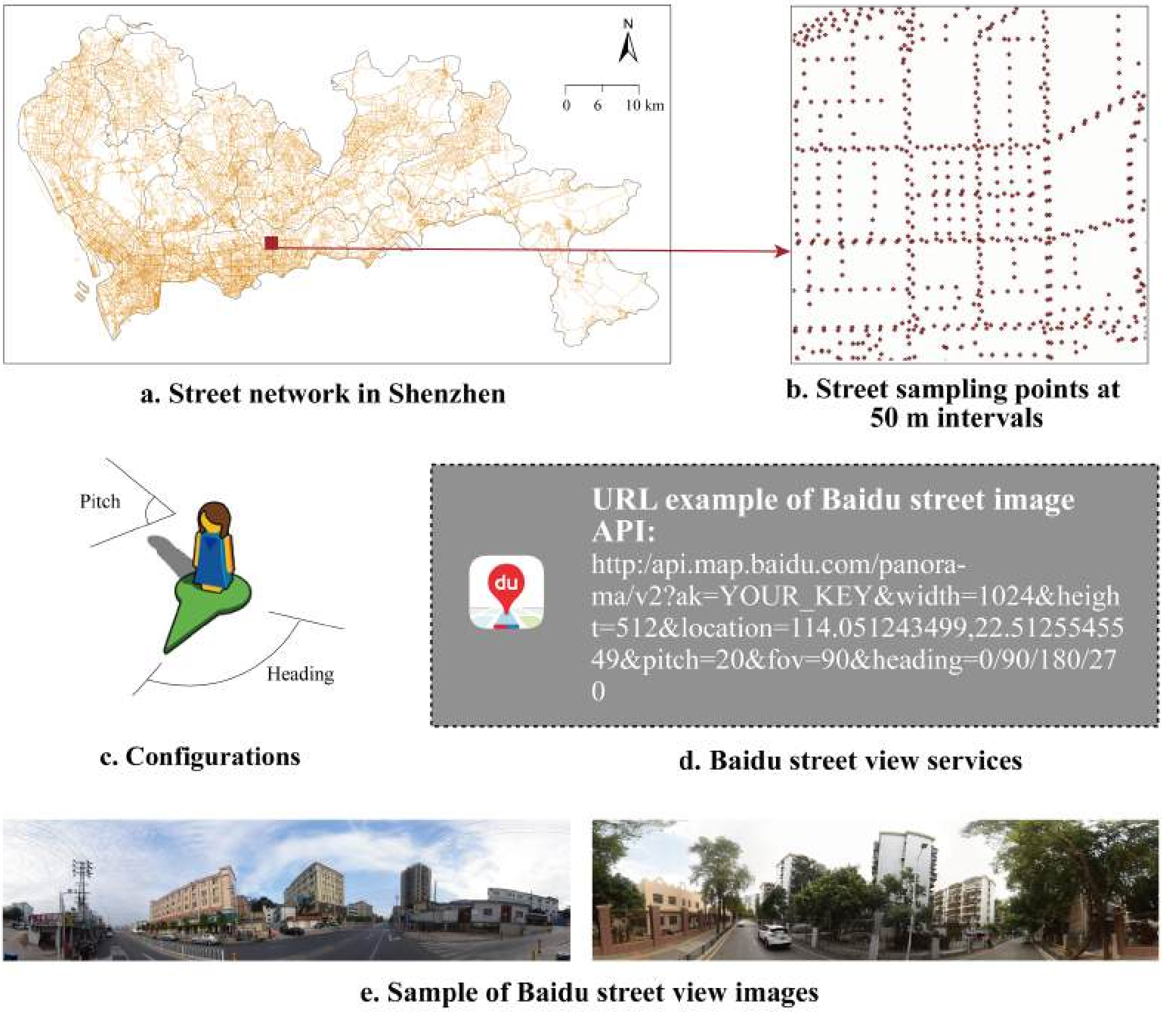


Figure 4.3: Collection of Baidu-SVIs.

jects. Its core innovations include the introduction of an encoder-decoder structure and atrous convolution strategy. The encoder extracts image features through a deep network, while the decoder upsamples these features to restore the spatial resolution of the image. Moreover, atrous convolution, also known as dilated convolution, allows the model to explore image content at different scales without increasing computational cost, thus capturing multi-scale information more effectively. The model was trained using the ADE20K dataset, a widely used image dataset specifically designed for image semantic segmentation and scene parsing tasks, created and maintained by researchers at the MIT Computer Science and Artificial Intelligence Laboratory (CSAIL). The ADE20K dataset includes a vast array of images from various environments and scenes, along with corresponding detailed pixel-level annotations. Its complexity and diversity are characterized by the rich objects and parts labeled within each image, covering thousands of categories and providing the necessary information for machine learning models to recognize and analyze complex scenes. This dataset encompasses not only common categories such as people, vehicles, and buildings but also more challenging small objects and fine scene details, such as furniture and decorative items.

The third step is the model's output, which consists of semantic segmentation results where different

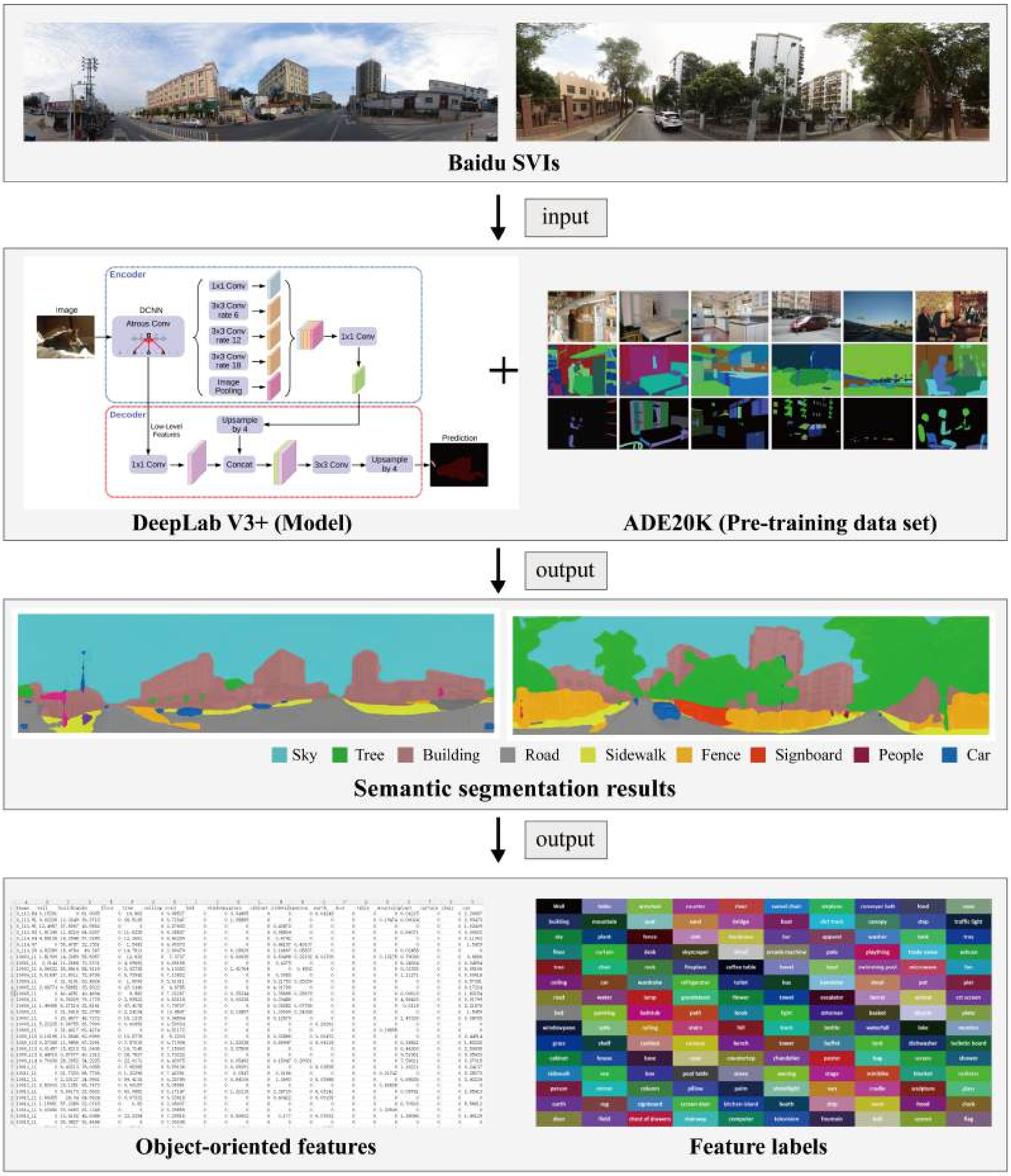


Figure 4.4: Semantic segmentation process.

colors represent different categories, such as sky, trees, buildings, roads, sidewalks, fences, signboards, people, and vehicles. These segmentation results clearly distinguish and identify the main objects and landscape features within the images.

The fourth step involves using the output semantic segmentation images to extract object-oriented features, such as the height of buildings and the coverage of trees. These features are then mapped to feature labels for further urban environment analysis and pattern recognition studies. The table below the images lists the feature codes and corresponding values for each object category, while the adjacent color label chart provides a clear visual reference for each color code, facilitating the understanding and cross-validation of the model's output. This method allows for an understanding of the urban environment's composition at a finer granularity.

4.3.4 Dynamic Tracking of Pedestrians in Publication IV

In Publication IV, YOLO v7 is utilized as a tool for detecting pedestrians on streets. YOLO v7, an advanced real-time object detection model, sets new benchmarks in speed and accuracy. Achieving the highest precision among real-time detectors at a speed of 30 FPS or higher on a GPU V100, it surpasses both transformer-based and convolution-based models. Trained from scratch exclusively on the MS COCO dataset without auxiliary datasets or pre-trained weights, YOLO v7 exemplifies robust, efficient learning.

The process is elucidated using static images rather than video. Figure 4.5 illustrates a deep learning-based image processing workflow for semantic segmentation and object recognition. Initially, a captured Baidu-SVI image is introduced into the system and undergoes pre-processing. It is then processed by the backbone of a deep neural network, comprising convolutional and batch normalization layers (CBM) for feature extraction.

Subsequently, the extracted features are forwarded to the head of the network, which includes complex structures like skip connections and upsampling layers to retain details during image segmentation. This section also integrates Global Average Pooling (GAM) and Spatial Pyramid Pooling (SPP or ASPP) modules, assisting the model in capturing contextual information at various scales.

In the final stage, the semantically segmented image is resized to its original dimensions. The output is one or more segmented images, each pixel labeled to indicate its object category, such as person, vehicle, or building. The output image highlights detected instances of the "Person" category from the original input, with the targets emphasized in different colors for ease of identification and analysis.

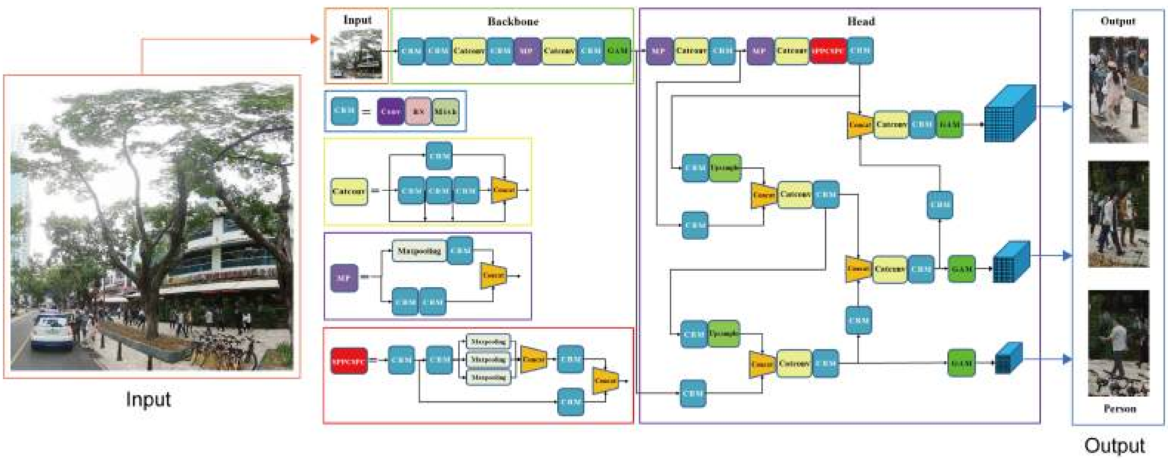


Figure 4.5: The structure of YOLO v7.

4.3.5 Quantification of UV Residents' Sentiments in Publication III

In the field of NLP, we have chosen the BERT model for sentiment analysis. The primary reason for the superiority of this deep learning-based BERT model over traditional models is its capability to dynamically adjust the sentiment interpretation of words based on the text in their surrounding context. The pre-trained BERT model is notable for its versatility, as it can be fine-tuned for various NLP tasks to suit different application scenarios. We grabbed the structure of BERT from the study of Devlin, Chang (Devlin et al., 2018) (Figure 4.6). To conduct sentiment analysis, a [CLS] symbol is added to the pre-trained BERT model, which is inserted at the top of the input text. BERT uses Transformer technology (Ke et al., 2017), which effectively applies the encoder-decoder model (Sutskever et al., 2014) and attention mechanisms to NLP tasks (Kim et al., 2017). In the supplementary material, we provided a sample of sentiment analysis, attention mechanisms, and model evaluation.

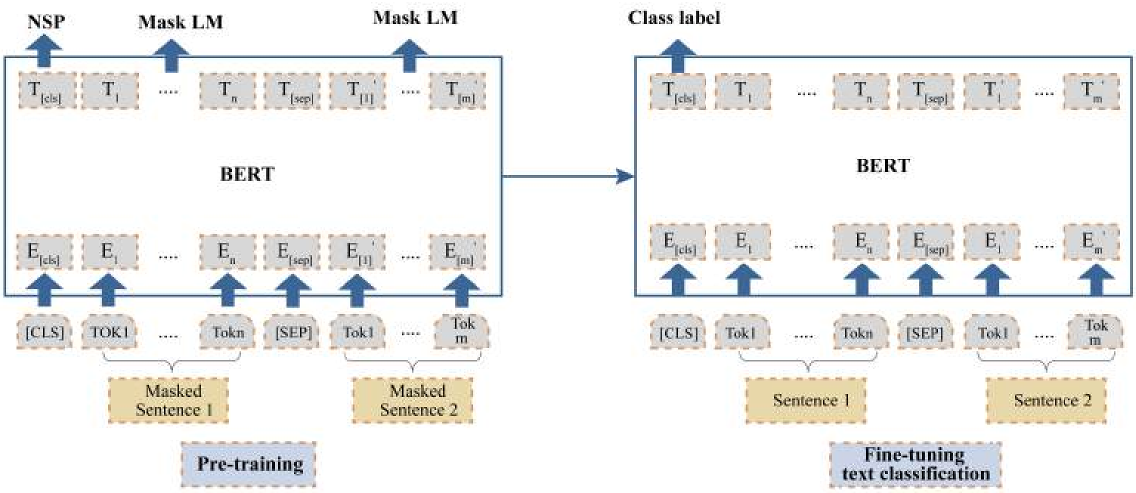


Figure 4.6: The structure of BERT.

We collected Weibo text data from the Sina Weibo website (https://m.weibo.cn/) over a period from June to December 2022 in the Shenzhen area. These data include not only the textual information but also the latitude and longitude of the posting locations, user IDs, and counts of retweets. By filtering based on geographical location, we obtained 981,678 data entries related to FSs and 519,269 related to UVs.

In our in-depth analysis, we specifically selected four keywords highly related to Socio-Economics: "UV", "residential", "neighborhood", to extract Weibo entries closely related to our research theme. Consequently, we extracted 93,110 entries from FSs and 42,540 from UVs. During this process, we utilized the "weibo_senti_100k" pre-trained model(https://github.com/SophonPlus/ChineseNlpCorpus/blob /master/datasets/weibo_senti_100k/intro.ipynb), specifically designed for Chinese sentiment analysis, which has shown excellent performance in tasks of this nature.

The sample and evaluation mechanism of sentiment analysis and the attention mechanism of NLP are presented in the appendix.

4.4 Research: Paper I to IV

Based on the theme of this doctoral dissertation, our research results have been published in the following articles:

- Article I: Conceptual analysis of innovative streets
- Article II: A case study of pedestrian-friendly urban design in Düsseldorf, Germany
- Article III: An in-depth case study of street environments in UVs and their relationship to residents' mental well-being
- Article IV: Exploring the potential mechanisms of micro-urban streetscape features on individual daily mobility through field surveys.

The interactions and how these four papers are integrated into my doctoral project are illustrated in Figure 4.7.

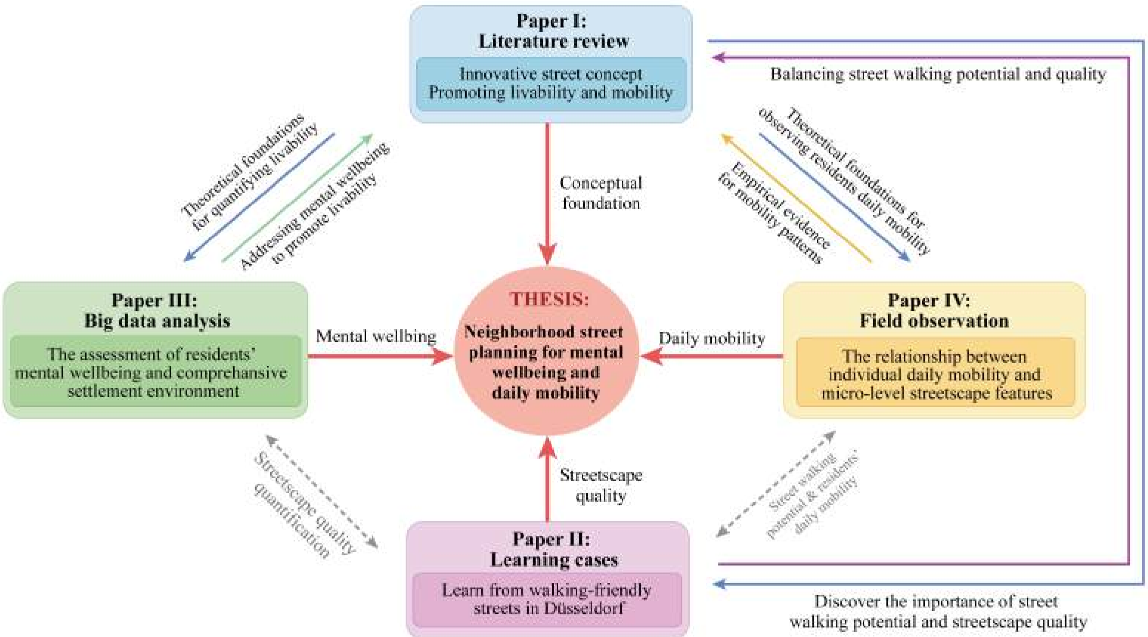


Figure 4.7: Relationships between the four papers and the dissertation.

I commenced my PhD project with an extensive and in-depth literature review in **Paper I**, aiming to comprehensively grasp the diverse functions and mechanisms through which innovative streets enhance traffic mobility and improve residents' quality of life. Drawing upon the insights revealed by this literature review, we selected Düsseldorf, Germany, as the empirical study setting to explore how street connectivity and the quality of streetscape spaces positively affect residents' travel behavior (**Paper II**). Building on an analysis of exemplary cases, we conducted big data analyses and thorough field studies on informal residential areas in China, focusing on two major issues: the impact of UV street environments on residents' mental well-being (**Paper III**) and their daily mobility (**Paper IV**).

Paper I highlights the dual role of streets in serving both transportation and social functions. It introduces an innovative analytical approach that links strategies to enhance the social attributes of streets with functional designs to improve commuting efficiency. Against the backdrop of increasingly competitive street space, by promoting the synergistic development of urban mobility and livability rather than exacerbating their differences, we can enhance the efficiency and vitality of streets. Building on this concept, **Paper II** explores the interactive relationship between the paradigm of deep learning-driven analysis of streetscape visual features and street walking potential assessment. This phase establishes a preliminary system for street quality assessment, emphasizing assessment from the pedestrian's perspective rather than top-down perspective. Further, **Paper III** leverages multi-source big data to refine the street assessment system, extending the consideration of street environments to the unique context of Chinese UVs. Through the collection of social media data, I assessed the mental health of UV residents and analyze its correlation with the street environment. Finally, **Paper IV**, through on-site observation, attempts to quantitatively analyze street space quality at a micro-scale. In this in-depth study, street morphology, drone technology, and object detection techniques are used to investigate how residents use UV streets. In short, **Paper I** establishes the theoretical framework for street analysis. The study of exemplary cases in **Paper II** provides a reference for the transformation of streets in informal settlements. By employing different quantitative methods, **Papers III** and **IV** empirically analyze the feasibility of enhancing street mobility and residents' well-being through street renovation in UVs.

Chapter 5

Publications

Article 1: Key facts and author contributions

Reference	Rui, J. and Othengrafen, F. (2023). Examining the role of innovative streets in enhancing urban mobility and livability for sustainable urban transition: A review. *Sustainability*, 15(7):5709
Contributions	RJ: 70%, OF: 30%
History	Submitted: 13 February 2023 Accepted: 21 March 2023 Published: 24 March 2023

Signature:

Jin Rui — Date

Frank Othengrafen — Date

sustainability

Review

Examining the Role of Innovative Streets in Enhancing Urban Mobility and Livability for Sustainable Urban Transition: A Review

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Abstract: As an essential component of urban public spaces, urban streets play a crucial role in shaping cities and promoting urban sustainability. This article focuses on innovative streets as a catalyst for sustainable urban transition. It reviews the theoretical discussions, and empirical evidence on innovative planning approaches for urban streets. For that purpose, measures related to innovative streets are divided into two broad categories: urban mobility and urban livability. The results indicate that integrating smart street facilities with the Internet of Things (IoT), adopting a combination of grid and radial street networks, and fostering a safe street environment are vital in promoting urban mobility. Conversely, a walkable, rideable, and human-oriented street environment enhances social interaction and urban livability. The street's dual function as a commuting and social space highlights the interplay between rising mobility and intensive street usage, leading to competition for street space. To mitigate these conflicts and advance sustainable urban transitions, enhancing street safety, reducing disparities in planning and user behavior, and accommodating the needs of all street users is crucial. Overall, the evidence supports the contribution of streets to sustainable urban transition.

Keywords: innovative streets; sustainable urban transition; urban mobility; urban livability; street review

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Citation: Rui, J.; Othengrafen, F. Examining the Role of Innovative Streets in Enhancing Urban Mobility and Livability for Sustainable Urban Transition: A Review. *Sustainability* **2023**, *15*, 5709. https://doi.org/10.3390/su15075709

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1. Introduction

1.1. Background

Cities and urban neighborhoods are at the frontline of sustainability [1,2]. They are most vulnerable to ecological, socio-economic, and political crises; on the other hand, they are innovative hubs for sustainability transitions, providing multiple actors with opportunities to jointly experiment and test urban practices to create and establish new sustainable systems and infrastructures [3]. In this regard, transitions towards sustainability entail socio-spatial processes to overcome lock-in effects and the path dependencies of previous developments through innovative ideas and approaches [4]. Accordingly, sustainable urban transitions are purposeful, systemic, long-term, and vision-led changes towards sustainability. They can be understood as goal-oriented processes initiated to achieve sustainable targets in a complex set of urban practices, technologies, infrastructures, markets, and institutions. This requires long-term oriented governance approaches and flexible, adaptive, and reflexive policy designs that help re-shaping, re-defining, and establish urban sustainability [2,5,6].

Sustainable urban transition thus involves reorganizing urban infrastructure, transportation, lifestyles, and neighborhood interactions to yield the co-benefits of urban efficiency and urban dwellers' well-being. Among these, sustainable urban infrastructure plays a critical role since the upgrade of public facilities and urban transportation has the potential to mitigate the adverse effects of climate change and urban sprawl.

Urban streets, as the backbone of urban infrastructure, serve a diverse array of functions, including transportation, recreation, socialization, and reproduction. Under the advocacy of Appleyard and Jacobs [7,8], streets progressively became a symbol of social places, taking on daily functions such as inhabitants' communication and social harmony. Despite the proliferation of street theories and approaches aimed at promoting urban sustainability through enhanced mobility and livability, a structured theoretical framework for using innovative street approaches to achieve sustainable urban transitions is yet to be established. Previous studies have partially examined the relationship between streets and active transportation patterns and the role of urban streets in increasing social resilience [9–11]. There is a lack of research on the relationships between street infrastructure, street network patterns, and traffic safety.

This review seeks to categorize innovative street design and measurement approaches while discussing the synergy of street mobility and livability to facilitate the sustainable urban transition. We aim to contribute to the field by filling the following gaps: (1) What are the theoretical perspectives and practical guidance on innovative street concepts that have been proposed? (2) What synergies and potential conflicts regarding sustainable urban mobility and urban livability on the street? (3) What considerations must be taken when planning and implementing innovative streets? The findings of this review have the potential to inform urban planners and decision-makers in creating sustainable and livable urban environments through innovative street design and management practices.

The review is structured as follows: The definition of innovative streets is elaborated in the remaining Section 1. Section 2 explains the research methodology and materials. Section 3 examines the current innovative street theory regarding urban mobility and livability. Section 4 critically discusses synergies, potential conflicts, recommendations, and principles for designing innovative streets. Section 5 provides the conclusion and further directions.

1.2. Definitions of Innovative Streets

As the arteries of the city, urban streets not only facilitate transport and commuting, they are also places for recreation and connectivity on different scales, with a commitment to enhancing urban mobility and livability [12]. Figure 1 illustrates how innovative streets emerge at the interface between sustainable urban mobility and urban livability and what characteristics and attributes are associated with it.

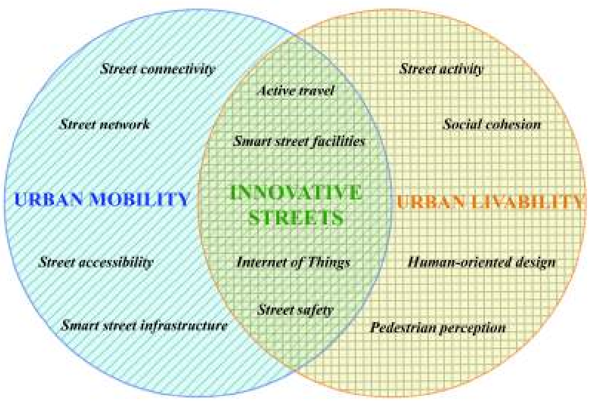

Figure 1. Innovative streets as an integrative urban practice.

2. Material and Methods

2.1. Research Scope and Search Strategy

The review concentrates on published articles in the Web of Science and Scopus databases. Only articles between January 2000 and May 2021 that were published in English journals were selected. As the conceptualization of innovative streets is not clearly defined, the scope is narrowed down to urban streets, which considerably impact social interaction and community cohesion. This allows data extraction in comparable settings [13]. Terms and keywords related to the concept of innovative streets also include synonyms such as "neighborhood street", "innovative street", "walkable street", "livable street", "sustainable street", "calm street", or "creative street" were searched as the first step. The search was not limited by street; therefore, synonyms such as "avenue", "boulevard", and "road" were included. However, synonyms with a tenuous connection to the street were excluded from the search due to the topic's divergence, such as "street crime" or "street sewage treatment". The second step was to relate the concept of innovative streets with urban planning and sustainability. Here, the different concepts combined with "sustainable urban transition" or "sustainable urban planning" to identify the correlation between innovative streets and sustainable urban transition; 444 articles met the set conditions.

2.2. Procedure and Data Extraction

The procedure for data extraction consists of two progressive steps (Figure 2). A review of the abstracts of all the articles was studied to determine if they contributed to the research topic. Particular classifications were used to select the most eligible articles:

- High level: the keywords, related terms/concepts, and conclusion of the article are highly relevant to both streets and sustainable urban transition. For instance, longitudinal research of neighborhood commercial streets in Boston has identified the relationship between physical street design, resident behavior, and urban livability [14]. Such publications contribute to the advancement of innovative streets.
- Medium level: the terms and concepts overlap with this review; however, there is sufficient content, such as case studies. Articles that examine design features for transportation or environmental purposes but do not consider street design as a means of increasing urban sustainability are considered to be of moderate relevance and are omitted.
- Low level: topics have little relevance to this review. Some papers concentrate on urban poverty and sewage management, with the street having a minimal role in the research. These articles are excluded.

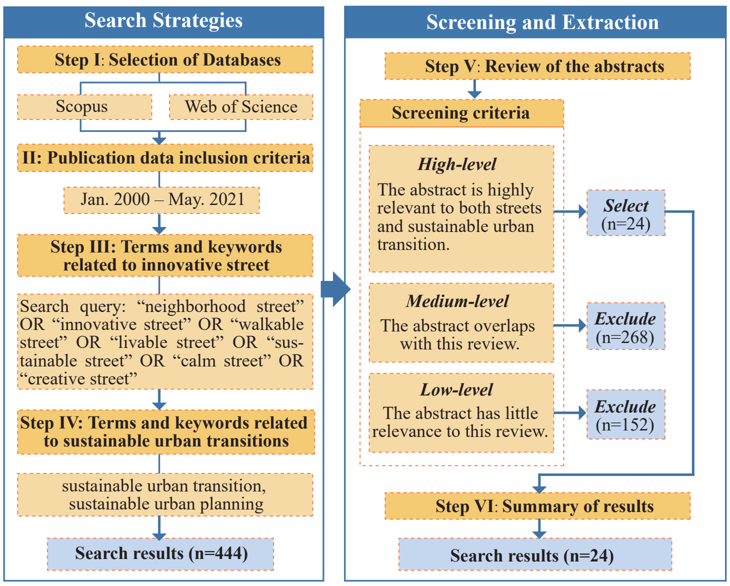

Figure 2. Flow chart of the applied process to select papers for this review.

Finally, 24 articles were selected for the analysis, dealing with innovative street approaches and sustainable urban transition.

3. Results

As shown in Figure 3, the high-frequency keywords were then identified and clustered using keyword co-occurrence analysis in Citespace. The specific keywords are then listed in Table 1, and six sub-themes were categorized into two clusters, i.e., urban mobility and livability, to explain the contribution to sustainable urban transition. Tables 2 and 3 compare these publications cross-sectionally by their research objectives, factors examined, and results.

The results of this study reveal a broad geographical representation among the selected papers, with a mix of global and regional perspectives. Four articles (16.7%) present a worldwide outlook, while eight articles (33.3%) focus on cities in North America, particularly the United States (seven articles). Europe is the subject of investigation in six articles (25%), while four (16.7%) explore cities in China. The remaining two articles (8.3%) address technical matters. Nonetheless, geographical similarities were discovered, with all studies selecting cities with a high level of development, such as cities in developed countries or major cities in developing countries such as Hong Kong. This may be due to the abundance of street pilot studies and readily available geographic information in these locations.

Figure 3. Results of a preformed keywords co-occurrence of the 444 articles reviewed on innovative streets related to sustainable urban transitions.

Table 1. Categorization of high-frequency keywords into six sub-themes.

Research Topic	Keyword Co-Occurrence Analysis	Sub-Themes
Urban mobility	Smart infrastructure, facilities, management	Smart street infrastructure
	Connectivity, accessibility, density, street hierarchy, street network	Hierarchical street network
	Safety, children, accessibility	Safe streets as a guarantee of access
Urban livability	Physical activities, social interaction, health, place making	Street activities to enhance social interaction
	Streetscape design quality, pedestrian, physical environment	Human-centered Street environment design
	Walking, cycling, sustainable transport, public transport, travel, electric vehicle	Active travel and its assessment criteria

3.1. Urban Mobility

The co-occurrence analysis of 24 articles indicates that the innovative streets related to urban mobility involve numerous aspects (Table 2). First, smart street infrastructure examines the current development of street infrastructure, creative practices, and on-street facilities. Second, hierarchical street networks elucidate the optimal network structure to maximize urban transportation efficiency. Third, safe streets synthesize macro-, micro-, and application-level commonalities in street safety design to ensure the accessibility of the street and the safety of the street users.

3.1.1. Smart Street Infrastructure

Sustainable urban transition aims to make optimal and sustainable use of urban resources. Well-equipped streets increase environmentally friendly travel and decrease the use of automobiles [15,16]. Our survey indicates that street infrastructure, including street parking, charging facilities, smart furniture, and smart lighting, will create opportunities for urban sustainability.

Street Parking

Marshall, Garrick, and Hansen [17] propose a combination of on-street parking with diverse land uses that provide convenience while stimulating retail businesses, which ensures accessibility to urban land and increases productive use. For better access to information about parking spaces, Gu et al. discovered that by applying wireless sensor networks to the street parking system (SPS) while proposing a state machine-based parking algorithm, the state of on-street parking can be managed efficiently [18,19]. The proposed SPS consists of a computer server, a base station, routers, end devices, and an LCD board. The high-precision parking algorithm and fast feedback in this wireless sensor network-based SPS promote the efficient use of street parking and redefine the land use of the parking area.

Street Charging Facilities

Plug-in electric vehicles (PEVs) are an effective alternative to gasoline-powered automobiles [20,21]. However, with the advent of new technology, travelers' dependence on charging stations has increased significantly. Grote, Preston, Cherrett, and Tuck [22] employed population and parking data to assist authorities in Southampton, United Kingdom, in identifying suitable places to install charging devices in residential areas. The study has shown that the installation of wireless charging via electromagnetic induction pads embedded under on-street parking spaces and on the undersides of vehicles, as well as the development of rapid charging stations in significant street parking areas, incentivizes citizens to adopt shared charging solutions and leads to the attainment of related environmental benefits.

Smart Furniture

Numerous studies have highlighted street furniture for its essential role as street infrastructure to enhance the comfort of pedestrian travel and outdoor activities [23]. In May 2016, New York City Commission announced the launch of a new pilot initiative involving the installation of multi-purpose benches to build a sustainable city [24]. These smart benches offer complimentary mobile charging, and interactive devices display geographic information about nearby amenities. They function as connection points for IoT to transmit data to terminals [19]. While walking on these streets, pedestrians grasp street amenities, urban functions, and transit routes.

Smart Lighting

Currently, there is power saving by providing street lighting with energy-efficient LED lights. Installing solar panels on street lights to collect solar energy and convert it to electricity can provide the city with additional environmental benefits. Additionally, through intelligent control systems for the IoT, smart lighting enables more precise dimming control and shorter run times than traditional street lighting [24]. Many street-smart lights provide a reasonable basis for installing sensors that connect to the IoT to deliver road information.

Table 2. Articles examining the correlation between innovative street and urban mobility.

I: Smart Street Infrastructure			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[24]	To explore the technologies and projects implemented in NYC for building a smart city.	• Water management • Link NYC • Smart lighting	• In 2014, New York City popularized free WiFi, ensuring unlimited phone calls, device charging, and access to city services and maps. • The use of energy-efficient LED street lights to provide better lighting and reduces energy waste. Through the installation of sensors, traffic, pollution, and crime data can be collected. • Street and pedestrian data are collected through sensors deployed on the street and uploaded to the cloud for processing and output for smart street planning strategies.
[17]	To grasp the full scope of on-street parking, involving demand model, land use, and environment.	• Parking demand • Pedestrian environment • Traffic speed	• Assessing on-street parking increases the value of urban land use, while ensuring enough land for productivity. • Low-speed zones will be built only when on-street parking is incorporated with other countermeasures into urban design.
[22]	Identify potential locations for the initial installation of residential on-street charging infrastructure for Plug-in Electric Vehicle in urban areas.	• Charging infrastructure • Plug-in Electric Vehicle	• The proximity to public transport access points, as residents with easy transit access may have reduced road vehicle requirements. • The provision of such infrastructure removes barriers to purchasing electric vehicles, thus contributing to the associated environmental benefits. • Encourage street infrastructure to achieve environmental benefits by determining the initial installation location of electric charging posts in residential areas.
[18]	Introducing a street parking system to help manage on-street parking in high-density cities.	• Wireless sensor networks • Street parking system	• A street parking system based on wireless sensor networks and a parking algorithm based on state machine are proposed to improve street parking efficiency. • The street parking system consists of a computer server, a base station, routers, end devices, and an LCD board. • The vehicle detection accurate rate of the SPS is nearly 99%; therefore, the proposed SPS is energy efficient.
[19]	Using sensors organized through the wireless networks to inspire the infrastructure construction of the smart cities.	• Wireless network • Smart city • Environment monitoring	• The primary monitoring network uses street lights as routing and cabs as dynamic nodes. Collected information will be sent to the designated terminals as messages. • A smart urban environment monitoring system based on the wireless network of ZigBee was designed to complete the real-time collection of urban environment information.

Table 2. *Cont.*

II: Hierarchical Street Network			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[9]	To explore how urban streets can support urban resilience.	• Street centrality and connectivity • Street network typology • Street width, edge, layout and orientation	• It requires a different level of centrality to take advantage of the economies and construct urban services and infrastructure. • The connectivity of streets is essential for urban resilience, reducing the dependence on the automobile and increasing accessibility of urban resources. • Narrow streets should be linked to wide streets by designing the street network with mixed hierarchies.
[25]	The aim is to examine the effects of physical environment variables on active travel and residential activities, including urban streets.	• Street patterns • Physical activities • Walking and cycling	• Residents from communities with higher density, greater connectivity, and more land use mix report higher rates of walking and cycling. • Connectivity is high when streets are laid out in a grid pattern, and there are few barriers (e.g., walls, freeways). • Route distance is comparable to straight-line distance with high connectivity. In addition to direct routes, grid patterns provide a choice to reach the same destination.
[26]	To clarify understanding of the different kinds of network representations and their hierarchical properties and to provide a way of capturing street network structure.	• Street hierarchy • Road network • Route structure	• A mathematical retrofit and clarification of relations between graph-based and route structure approaches are proposed. • Street network structure is interpreted in terms of hierarchical relations. • Road hierarchy is of definite concern to road network design and management. • Continuity, connectivity, and cardinality could create a formal hierarchy of streets.
[12]	To assess the configuration and sustainability of street networks in China's superblocks.	• Route structure • Street connectivity • Street continuity	• The suitable streets for connectivity and sustainability are a combination of fine orthogonal grids and multiple sets of radiations that avoid the disadvantages of monotony. Nonetheless, the resulting triangular plots reduce functional adaptability. • Bottom-up, resident-led streets and semi-public spaces are narrowing the gap between different urban blocks.
III: Safe Streets as a Guarantee of Access			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[13]	To summarize the literature on the relationship between the built environment and traffic safety in the urban area.	• Traffic safety • Street network design • On-street parking • Street width	• The traffic environments of the dense urban environment appear to be safer than the lower-volume environments of the suburbs. • Less forgiving design approaches such as narrow lanes, traffic-calming measures, and street trees near the roadway improve safety performance in a dense area. • Create "clear zones" between sidewalk and roadway; adding street furniture and trees in this area helps reduce traffic collisions.

Table 2. *Cont.*

III: Safe Streets as a Guarantee of Access			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[27]	To determine the effect of street built environment characteristics on pedestrian safety.	• Cycle lanes • Street geometric • Street network • Sidewalk width • Paving quality • Street lights • Path slope	• The fundamental factor in street safety is speed. • On-street parking, the number of lanes, and the separation of pedestrians from the roadway result in increased danger of accidents. • The physical separation of the street prevents cars from the sidewalk and improves the streetscape but decreases the view and visibility of pedestrians. • Street parking requires a buffer zone to ensure pedestrian visibility, which can be achieved by narrowing the lane width.
[28]	To assess the effect of street and street network characteristics on street safety.	• Street connectivity • Street network density • Street network patterns	• High-density street network results in low collision rates due to travel patterns. Neighborhoods with a higher density of intersections have a lower percentage of residents who travel by automobile. • Increased intersection density is associated with a reduction in severe crashes due to lower vehicle speeds. • Increased intersection density, on-street parking, and bike lanes along streets contribute to lower vehicle speeds and improve street safety.

3.1.2. Hierarchical Street Network

The characteristics of streets conducive to sustainable urban transition are generally summarized as follows: high connectivity that provides circulation efficiency, high complexity that reinforces centers and responds to the demand of daily life, and suitable depth that ensures a reasonable distance from any place in the street to the nearby facilities [29]. The hierarchical structure of the street network represents a multi-scale classification of daily activities and urban efficiency. It should be meticulously planned and strictly regulated to establish a framework that enables sustainable development while facilitating bottom-up renewal within an appropriate hierarchy [12].

Using a mathematical retrofit and clarification of relations between graph-based and route structure approaches, Marshall [26] emphasized the impact of the different continuity and termination of streets through junctions on the street hierarchy rather than "node-centric". He clarified that any properties of continuity, connectivity, or cardinality, suitably ranked or combined, can create a formal hierarchy of streets. Saelens, Sallis, and Frank [25] suggested that a network of streets with a grid pattern without barriers results in superior connectivity and better traffic efficiency, providing more route options for pedestrians, cyclists, and drivers. Sharifi [9] compared the performance of gridded and dendritic networks and found that well-connected streets exhibit characteristics of both typologies, featuring a hierarchical pattern of centrality distribution and cross-connections. A scale-hierarchical street design allows for greater adaptability to changing conditions and enhances the connectivity and complexity of urban streets in their interactions with other urban functions [9,26].

Findings have been derived to enhance the efficiency of urban mobility. Ge and Han [12] leveraged Marshall's street path analysis model to identify the attributes of the most sustainable streets, which were found to have fine orthogonal grids and abundant radiations. The study highlights that a "small block and dense network" approach can offer high connectivity and enhance the linkages between communities and cities, and is closely intertwined with the macro-scale street network that is pivotal to the sustainable development of urban transportation, commuting, and daily activities.

3.1.3. Safe Streets as a Guarantee of Access

The relationship between street network typologies and urban street safety has been analyzed in macroscopic studies. The findings support the notion that street networks with loop and lollipop forms are safer than gridded street networks [30–32]. Furthermore, the density of intersections plays a significant role in travel decisions, and driver behavior since high-density intersections lead to fewer and relatively minor car crashes [33]. This correlation is further demonstrated by the observation that neighborhoods with higher intersection densities also tend to have a lower percentage of residents who commute by car. High-density residential streets can disperse congestion on arterials, allowing cities to build arterials with fewer travel lanes while providing more space for walking and cycling [13,28].

The microscopic study discusses the coexistence of roadways, sidewalks, and on-street parking. The views are controversial. Ewing and Dumbaugh [13] advocated spatial separation between sidewalks and roadways by creating broad “clear zones” and adding street trees, concrete planters, and other fixtures to reduce vehicle-to-pedestrian collisions. Conversely, opposing views indicate that these physical separations led to hazards by reducing the visibility of pedestrians, especially for children and the elderly [27]. The issue of on-street parking is equally controversial in terms of street safety, with Congiu, Sotgiu, Castiglia, Azara, Piana, Saderi, and Dettori [27] pointing out that on-street parking increases the risk of crashes by two times, and the cause of car–bicycle collisions is unexpected “dooring.” Nevertheless, on-street parking has been shown to improve traffic safety since it is used to buffer the pedestrian realm from potentially dangerous oncoming traffic and to clarify the spatial configuration of the public right-of-way. Another supportive argument shows that the low speed when parking reduces accidents’ severity [28]. The contribution of the “clear zones” between sidewalks and roadways and on-street parking to street safety remains a topic of study. It requires examination across diverse urban environments, such as high-density and low-density areas.

3.2. Urban Livability

While urban streets have the potential to drive sustainable urban transition regarding urban efficiency, travel experience, street infrastructure, and user safety, they also serve as open urban public places that facilitate social interaction and everyday activities. Section 3.2 looks at how urban streets operate as social places.

3.2.1. Street Activities to Enhance Social Interaction

The great potential for social inclusion and interaction is at everyone’s doorstep, and the streets are a great place for social integration [34]. This implies that inhabitants may engage in the street, directly and indirectly, increasing both stationary and continuous activity. These short-term, low-intensity possibilities for easy engagement represent the start of longer-term encounters and signify that the street serves as a public space. A significant body of literature underscores the street’s role as a learning environment for children, providing exposure to various people and activities. Beyond its educational benefits, the street also serves as a site for adult learning since street users can be motivated to engage in new activities by watching other interactions [35–37].

Biddulph [37] examined urban neighborhood streets in seven home zones in the UK to investigate the role of livable streets in encouraging users’ activities. It was found that children were the primary beneficiaries of livable streets, engaging in play activities with relative freedom across the entire area. Adults were also observed spending extended periods on the streets responding to children’s presence. Sauter and Huettenmoser [34] explored the relations between street design, traffic, and social interaction. The study discovered that streets with slow-moving traffic, limited parking space, and positive environmental qualities offer a significant opportunity for personal encounters and urban relations. This aligns with the conclusions drawn by Biddulph [37], who highlighted the significance of the street structure, such as layout, and speed restrictions, in promoting social interaction and inclusion. In this regard, street structure emerged as a more critical factor than social structure in fostering social integration.

However, as streets become scarce, they often conflict with their mobility purpose while reflecting their social functions. Streets epitomize the struggle to accommodate functions of "efficient" and "fast" but also "sustainable" mobility, as well as public space functions that include lingering and social interaction [38]. To address this challenge, Von Schönfeld and Bertolini [38] proposed recommendations at both the planning and governance levels. At the planning level, enabling more flexibility would allow public spaces in general and urban streets, in particular, to better adapt to changing roles. At the governance level, the involvement of residents and stakeholders in the street design process and the promotion of collaboration between the community and government are essential to achieve the desired outcomes.

3.2.2. Human-Centered Street Environment Design

The physical environment of the street influences street activities and even subtle environmental features significantly impact the experience of street users [23,39,40]. Urban design literature identifies human-centered qualities that enhance active travel, and these qualities act as a mediating factor between physical features and pedestrian behavior. In essence, to promote a sustainable transformation of urban space, understanding the public environment, including the street, as a combination of behavioral and physical environmental patterns is proven valuable.

Table 3. Articles examining the correlation between innovative street and urban livability.

IV: Street Activities to Enhance Social Interaction			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[35]	To enhance the value of the urban street as a social place.	• Route choice • Street aesthetics • Traffic and environmental safety • Diverse land use	• High-quality street environments such as convenient pavements and trails encourage residents to travel. • There will be a more pleasant social atmosphere and more aesthetically pleasing streets when there is less car traffic and less street incivility. • People are more attractive to people. Street users enjoy seeing people enjoying themselves, which enhances street communication.
[37]	To understand whether streets designed to be more livable encourage more diverse street users and activities.	• Home zones • Urban livability • Neighborhood streets • Shared space	• Different people use healthy streets for a variety of activities. • Well-designed streets will balance their competing requirements. • Streets with high design quality in home zones tend to be most friendly to children, where they are free to engage in activities. More adults will spend time here responding to the children and family. • Vibrant streets need to be permeable to pedestrians and bicyclists.
[34]	To discuss how street design and traffic affect social relations in urban neighborhoods.	• Social integration • Urban neighborhoods • Street livability • Traffic-calming	• The neighborhood streets are active social places. Streets with slow-moving traffic, limited space for parking, and good environmental qualities offer potential for personal development, contentment, and social inclusion. • The influence of the street structure, i.e., layout, speed limit, and design, is more important than that of the social structure. • The streets are great places for social integration, where children learn the language and where neighbors get into contact with each other.

Table 3. *Cont.*

IV: Street Activities to Enhance Social Interaction			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[38]	To clarify the significance of mobility functions and public space in urban streets for sustainable urban transition.	• Urban street • Social place-making • Urban mobility • Sustainable transition	• Mobility and public space are crucial elements determining the vitality of cities. • Enabling more flexibility would allow public spaces in general and urban streets, in particular, to better accommodate the various and shifting roles. • Governance takes the shape of participation, where different stakeholders are involved in decision-making processes. Participatory processes of planning have become imperative.
V: Human-Centered Street Environment Design			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[14,41]	These two studies address the relationship between social behavior and street environmental quality.	• User behavior • Physical street characteristics	• A high-quality street environment encompasses an adequate number of seating, pavement, street furniture, shade, and permeable and personalized street fronts that encourage people to congregate. • Street seating is conducive to pedestrians engaging in stationary activities. • Streets as public spaces create liveable neighborhoods; therefore, social, physical, and usage dimensions must be considered.
[40]	To analyze users' behavior in the street space and the interaction with physical street settings.	• Land use along the street • Street type • Users' behavior • Physical environment in streets	• Wide sidewalks, balconies, curbs, and street speed limits can improve walkability and accessibility. While multi-functions such as shopping malls, office blocks, and residential areas facilitate walkability. • Safety hazards are hidden in a high level of the walkable and pedestrianized area. Multi-street facilities and free access lead to street congestion. • To provide buffers between sidewalks and lanes, offering crosswalks could ensure street safety. • Safe connections between neighborhoods and special features should be considered to meet the basic needs of street users.
[23]	To propose flexible design principles for improving the flexibility of street furniture.	Standardization, suitability,adaptation, management, and safety of street furniture	• Community streets in urban areas suffer from excessive standardized street furniture, which cannot adapt to changing street conditions. • Urban characteristics and local identity are lost as a result of standardization. • Flexible street design principles are proposed: Custom in use, multifunctional use, respond effectively to changing circumstances, easy and conveniently managed, universal in use, and sustainable in use.

Table 3. *Cont.*

VI: Active Travel and Its Assessment Criteria			
Reference	**Objectives**	**Factor(s) Examined**	**Results**
[42]	To summarize the relationship between cycling and built environment characteristics.	• Cycling purpose • Built environment factors	• The presence of cycle paths and bike facilities was conducive to commuters and general cycling. • Mixed land use, availability of cycleways to non-residential destinations, and topographic gradient have less effect on cycling behavior in the urban context.
[43]	To offer visual assistance for identifying areas where modifications are required to enhance sustainable travel.	• Bicycle-route density • Bicycle-route separation • Topography	• A bikeability index was created to characterize and map a region's suitability for cycling, which can be applied for further research on health disparities referring to physical activities and urban street environments. • The index comprised five factors to positively influence cycling behavior: bicycle facility availability, bicycle facility quality; street connectivity; topography; and land use.
[44]	To outline a bicycle route choice model to advocate a better cycle-friendly street environment.	• Street infrastructure • Intersection control • Traffic signals • Bicycle lanes	• Cyclists are concerned with distance, frequency of turns, control of intersections, and traffic volumes; the presence of street-side cycle lanes, traffic calming measures, and high street connectivity are valued. • The treatment of intersection signals must be determined by the traffic volumes.
[15]	To evaluate walkability through GIS and street auditing indicators.	• Connectivity • Convenience • Comfortability • Conviviality • Conspicuousness • Coexistence • Commitment	• Mixed land use, high-density intersections, and well-connected streets are vital to boosting walking by reducing access distances. • Other modes of public travel offer more route choices and encourage active commuting. • It is important to involve stakeholders and decision-makers in selecting key concerns and avoid a simple additive equation of indicators.

The human-centered approach to street research focuses on user behavior, street area, and street facility. Gehl [36] claimed that dynamic and static pedestrian activity is a criterion for determining whether a street is human-centered. He suggested that the street's physical environment must provide static and mobile support. Mehta [41] argued that physical, land use, and social dimensions are critical in understanding urban streets to achieve human-centered streets conducive to stationary, lingering, and social activities Meanwhile, Do, Mori, and Nomura [40] classified resident behavior as accessibility, trading, idling, service, maintenance, and relaxation to examine the triadic relationship between user distribution, behavior, and the street physical environment in support of street management and social sustainability. By analyzing dense streets in Hong Kong, Siu and Wong [23] presented flexible street design principles, including custom in use, multifunctional use, responding effectively to changing circumstances, being quickly and conveniently managed, universal in use, and sustainable in use.

Human-centered street design characteristics (Table 4) are more than their physical components since they have a cumulative effect more remarkable than the sum of their parts [45].

Table 4. Human-centered street design approaches.

Elements	Theoretical Findings
Street width	• Wider streets increase evacuation capacity [46,47]. • Wider streets are suitable for integrating various modes of transport (e.g., bus or bicycle lanes, footpaths, etc.) [48]. • Less active transportation is expected along wide arterial roads that prioritize vehicle movements and do not provide adequate street tree protection [49].
Sidewalk	• Wider sidewalks can facilitate a variety of behaviors while also improving street connectivity and social interaction [40].
Seats	• Well-designed street seating is beneficial for walking [35]. • Ample seating is more beneficial for people when there are activities on the street [41]. • Seats are essential for pedestrians' stationary activities because people tend to sit most where there are places to sit [14,50].
Railings	• Fixed railings decrease the freedom of pedestrian movement [23].
Curbs	• Stationary activity occurs in places such as curbs, railings, and shaded areas [51]. • Metal and concrete railings are prone to secondary injuries after traffic accidents [23]. • Curbs bring more walkability and accessibility [40].
Street signage	• Adequate commercial signage is a distinctive feature of a pedestrianized street [39]. • Signage helps to create an area with high accessibility that is easy to enter and navigate [40].
Street green	• The shade produced by the street trees facilitates the gathering of street users [41]. • Trees, similar to other features, can play a central role in enhancing street livability [8,52]. • Street trees provide shade and reduce temperatures, which improves walking and thermal conditions [53].

3.2.3. Active Travel and Its Assessment Criteria

The street is inseparable from traffic, particularly active modes dominated by walking and cycling. Traditional research on street walkability is mainly based on field research combined with GIS data analysis. Measurement methods have become diverse owing to the accumulation of theory and technology development. According to the 3-Ds (density, diversity, design) for travel demand [54], Ewing and Handy [55,56] proposed the 5-Ds (density, diversity, design, distance to public transport, destination accessibility). Likewise, the 7-Cs criteria [15], i.e., connectivity, convenience, comfortability, conviviality, conspicuousness, coexistence, and commitment, were proposed based on the multidimensional 5-Cs (connected, convenient, comfortable, convivial, and conspicuous) by London Planning Advisory Committee [57]. The 7-Cs is a collection of the neighborhood and street-level variables that overlap substantially with the D-variables. Common findings indicated that mixed land use, high-density intersections, and well-connected streets are crucial to boosting walking by reducing access distances [15,54].

The measurement of street walkability has developed a robust framework, yet there are limited tools for evaluating a bicycle-friendly street environment. Broach, Dill and Gliebe [44] presented a demand model and route-finding tool for predicting bicycle travel based on GPS data. They found that cyclists are sensitive to distance, turning frequency, gradient, junction control, and traffic volume. Enhanced community bike lanes with traffic calming measures promote cycling volumes. Winters, Brauer, Setton, and Teschke [43] classified measuring techniques into five categories: cycling facility availability, bicycle facility quality, street connectivity, topography, and land use. The flexible parameters and weighting scheme of the approach enable users in other cities to modify it to their specific circumstances.

Additionally, conflicts exist between walking and cycling in the configuration of street space [42]. The heterogeneous street environments created by a mix of land uses may be conducive to walking, which may negatively impact the speed and safety of cyclists. Bicycle sharing stations often conflict by taking up pedestrian lanes and squeezing blind spaces. Further investigation is needed to examine the impact of modifications to the built environment of streets on active transportation and the mitigation of potential spatial conflicts between walking and cycling.

4. Discussion

4.1. Synergies and Potential Conflicts

The synergistic effect of urban mobility on livability encompasses the following elements: (1) A safe street environment is a prerequisite for community interaction to occur. Traffic calming measures and slower travel speeds encourage increased street activity and safety, which allows for greater visibility and mobility for pedestrians and cyclists; (2) street buffers enhance neighborhood safety by increasing pedestrian traffic and social interaction. Street buffers refer to physical separations between sidewalks, roadways, bike lanes, and waiting areas at intersections; (3) smart urban infrastructure and green traffic patterns result in an attractive street environment. Use electric and low-emission transportation modes to reduce urban air pollution and community noise pollution; (4) street hierarchy is central to the design and management of urban street networks. A multi-level urban street network formed by the combination of fine orthogonal grids and multiple sets of radiations maintains the high-connectivity advantage and responds to the diverse demands of daily life; (5) the integration of diverse modes of public transportation, including metro systems, public buses, bike-sharing programs, and car-sharing services, is essential in enhancing street accessibility and fostering incidental encounters. The availability of multiple travel options promotes socialization and provides individuals with greater flexibility and independence in navigating the city.

Urban livability and mobility are interdependent, impacting the other in significant ways. Regarding enhancing urban mobility, urban livability works in the following ways: (1) Vibrant streets encourage active travel behaviors. Human activity is attractive to others [36]. Individuals are more likely to choose walking when there is a presence of social interaction or recreational activities in the street environment; (2) the presence of street activities also helps to improve safety through a reduction in vehicle speeds. Drivers slow down when there are more pedestrians and activities on the street based on their perception of the street environment [28]; (3) frequent street activities catalyze the construction of shared facilities, such as bike-sharing. The provision of these facilities meets the commuting and social needs of participants, promoting a more livable and sustainable urban environment.

Mobility patterns and public space usage are inextricably linked since rising mobility and more intensive use of public space feed off one another and directly compete for ever-scarcer urban space. They exemplify the competition to balance "efficient" and "fast" mobility functions with public space activities such as lingering and social interaction [38], which is reflected in roadways, on-street parking, physical street separation, and street activities as follows:

(1) Reducing the number and width of roadways for safer neighborhood intersections results in lower travel speeds, but also exacerbates traffic congestion. The compression of lane space leads to increased crossing times for drivers and waiting times for pedestrians, diminishing the efficiency of street mobility.
(2) While low speeds in on-street parking can improve street safety, it can also contribute to urban congestion [40]. The presence of parking automobiles might interfere with moving vehicles and passing pedestrians by obstructing the view of each other from the driver and pedestrian [13,17,58]. Unexpected "dooring" during on-street parking threatens cyclists and pedestrians [13].
(3) Physical separation improves street livability and accessibility by providing a comfortable passing experience for walkers and cyclists. Nevertheless, when high traffic volumes come, separated strips can decrease commuter efficiency as the space occupied by the separation could have been utilized for additional transportation lanes [58].

4.2. Recommendations for Designing Innovative Streets

We advocate for innovative street design strategies to create sustainable and livable urban environments. These strategies are critical for making urban spaces more accessible, safe, sustainable, and socially engaging. By implementing these approaches, urban streets can prioritize people over cars, encourage sustainable mobility, and ultimately enhance the quality of life for residents.

4.2.1. Smart Street Infrastructure

Installing smart street amenities such as smart parking, charging stations, and citywide WiFi is highly recommended to enhance the experience of both drivers and pedestrians, making urban streets more convenient and user-friendly. Developing smartphone applications that utilize car GPS to provide real-time updates on parking availability at street intersections is another effective way to increase convenience and reduce traffic congestion. Such applications can help drivers easily locate parking spots, saving time and energy. To promote sustainable transportation, it is also recommended to increase the number of shared urban bicycles with fixed sharing points, encouraging more people to use bicycles for daily commuting and reducing traffic congestion. These measures support the transition to sustainable mobility, reducing carbon emissions and promoting a more sustainable transportation system.

4.2.2. Hierarchical Street Network

To improve street connectivity, grid network patterns without barriers and hierarchical dendritic patterns are recommended. Compared to dendritic networks, grid networks are less susceptible to potential disruptions in certain parts of the street. Additionally, it is suggested to reform the dendritic pattern to improve its connectivity by adding pedestrian/bicycle lanes to connect dead-end roads to other streets in the network. Increasing redundant connections in the street network is also encouraged to provide accessibility of service. Furthermore, promoting mixed-use development around highly concentrated street nodes/connections is an effective way to increase the vibrancy of the area. Appropriate pedestrian space reductions on centrally placed and pedestrianized streets could be transformed into one-way access for automobiles, enhancing car access to pedestrian zones and overall traffic efficiency.

4.2.3. Safe Streets as a Guarantee of Access

In urban district bureaus with high residential density, it is essential to prioritize pedestrian safety and comfort. One effective way to achieve this is by ensuring that sidewalks are as wide as possible and provided on both sides of the street. Additionally, distinguishing bike lanes from motorways through the use of white lines or broader buffer strips can increase safety for cyclists. To further improve safety, it is recommended to eliminate on-street parking space close to the intersection. This ensures that drivers and cyclists are visible to each other, reducing the risk of accidents. Mitigating turning conflicts at intersections can be achieved through the use of mixing zones, signal-protected turns, offset crossings, or bicycle-only waiting zones. Allocating space for communities or transport can also be achieved through reducing lane widths or removing under-utilized lanes. Lighting is another crucial aspect of street design that significantly affects safety and comfort. Therefore, improving the overall lighting environment of the street with street lights fixed to the appropriate building façade can significantly enhance pedestrian safety. To ensure safety and order at intersections, "corner quadrants" can be set up. Only elements related to safety, lighting, and traffic control infrastructure can be sited within the corner quadrant.

4.2.4. Street Activities to Enhance Social Interaction

In order to enhance the pedestrian experience and encourage social interaction, it is essential to provide adequate supportive facilities and equipment. The provision of public recreational amenities such as benches and railings should be determined based on the function and spatial capacity of the street. Additional seating should be made available to allow crowds to sit together and engage in various forms of social interaction. Shade and shelter, as well as street greenery, play a vital role in determining pedestrian activity levels. These amenities can provide a respite from the sun, rain, and wind, and also create a more pleasant environment for pedestrians. Additionally, the street hierarchy is another critical factor in promoting pedestrian interaction. Primary and secondary street pedestrian spaces should be supplied with a diverse range of street amenities that cater to different scales of activity. A tailored approach that considers the specific needs of each street should be taken, with amenities designed to complement the function and character of the street.

4.2.5. Human-Centered Street Environment Design

Improving human-centered street environment design is a crucial component of creating livable and sustainable urban environments. One key consideration is the appropriate buffer width between traffic lanes, which should be scaled based on the volume of traffic and condition of the street. On residential streets with lower traffic volumes, narrow buffers are adequate. However, for streets with higher motor vehicle speeds and volumes, wider buffers are necessary. Another important factor to consider is the street width. Appropriate street widths play a critical role in facilitating evacuation, creating multi-modal streets, accommodating technological transitions, and adapting to changing conditions. Calculating the right width involves considering the geometry of the street canyon, such as the aspect ratio, and the population density of the community. Modifying street edges through streetscape improvements is also crucial to ensuring that streets serve transportation, accessibility, and socioeconomic purposes. For instance, streetscape improvements can help increase the permeability of the street façade and create a visually appealing and welcoming environment for pedestrians and cyclists. Enhancing visual and physical openness and continuity between interior and exterior spaces can also help to create a sense of community and belonging among residents.

4.2.6. Active Travel Behavior

To improve mobility and reduce reliance on personal vehicles, it is important to increase the number and quality of transport modes available to residents. This includes not only buses and subways, but also shared bicycles and vehicles. By promoting alternative modes of transportation, cities can reduce congestion and air pollution while also providing greater access to key destinations throughout the urban landscape. In addition to expanding transportation options, it is also critical to design physical separations between the carriageway and the bicycle lane. This helps to improve safety for cyclists and reduce the risk of accidents. By providing dedicated cycling infrastructure that is separated from vehicular traffic, cities can encourage more people to bike for transportation, recreation, and exercise. Furthermore, creating accessible infrastructure is another key consideration in enhancing street inclusion. This includes the addition of handrails, accessible ramps, and Braille signs, among other features. By making streets more accessible to people of all abilities, cities can promote a more inclusive and equitable environment for everyone.

4.3. Principles for Further Research

Developing research guidelines facilitate theoretical development for innovative streets and sustainable urban transitions. The following principles provide further illumination for street studies.

First, streets should be identified as places for access, commerce, leisure, activity, and socialization. The structure and capacity make the street a complex public space with the attributes of both transportation and social functions. Accordingly, addressing urban mobility and other physical characteristics alone is inadequate if the social and economic role of the street is overlooked. A limited body of literature focuses exclusively on the social features of streets and their relationships with urban dwellers without adequate consideration of their transit capacity. In this respect, this review stresses the importance of having the multiple identities of the street recognized simultaneously, as their transportation characteristics contribute to a higher level of urban efficiency and safety. In contrast, their social characteristics contribute to enhanced neighborhoods and increased social activity. Developing a balanced approach to mobility and livability within a limited street area will contribute to a sustainable urban transition.

Second, policymakers and urban planners should recognize that street users make their behavioral judgments, which may result in deviations between expected planning results and street reality. Equally, users tend to choose active street environments that are positive for them as places to socialize and reflect the same tendency when choosing transportation routes.

Third, the importance of considering users of all ages and abilities cannot be overemphasized. An active pedestrian environment for healthy adults may be poor or even inaccessible to seniors or the disabled [14,15]. The street is a public space for all citizens, not exclusive to specific users. As a public space that serves all citizens, the street must offer diverse and flexible functions and comprehensive amenities to accommodate the needs of a wide range of users. Hence, research on streets, neighborhoods, and livable cities must prioritize increasing the diversity of neighborhoods and demographic samples under examination.

Fourth, the development of assessment systems needs to be transformed into a supportive tool for participatory decisions. This necessitates the participation of stakeholders, decision-makers, planning authorities, and street users in selecting key questions and weighing indicators to prevent simple additive equations. The assessment system should be closely aligned with practical applications to guide design practice.

4.4. Limitations

This paper has several limitations that should be acknowledged. Firstly, the paper has not been able to provide an in-depth analysis of the various types of urban streets. Pedestrian streets, traffic arterials, and neighborhood streets all serve different purposes in the urban system. It is essential to conduct further research that examines the nuances of different types of urban streets and their specific roles in varying urban contexts. Secondly, the methodological search filter we used has restricted our ability to comment on a broad range of articles. Our analysis has focused on 24 key articles that were primarily quantitative in nature and based on data acquired from major cities in developed countries. Therefore, the study lacks attention to small and medium-sized cities as well as cities that are relatively lagging in development. Thirdly, while the study does touch on important social and mobility-related identities associated with urban streets, it does not explore other aspects such as ecological resilience that contribute to sustainable urban development. Future research should aim to examine a wider range of factors that contribute to the identity and role of urban streets in shaping urban environments.

5. Conclusions and Further Directions

This review critically evaluates key articles in the field of innovative urban streets using rigorous selection criteria and provides a comprehensive discussion of their specific contributions to urban sustainability. While previous studies have tended to focus on single characteristics of urban streets, our review proposed a novel approach by linking mechanisms that promote the social attributes of streets with the design of features that facilitate efficient commuting. Our analysis of the intricate identities of urban streets and our approach to bridging conflicts resulting from these diverse identities marks a significant breakthrough that sets our work apart from existing studies. Building upon this foundation, we proposed a suite of innovative design methods and principles for urban streets, including measures to enhance street safety, an all-age consideration principle, a reality-aligned decision-making approach, and a participatory approach to decision-making that offers concrete design guidelines.

The ultimate goal of this study is to achieve sustainable urban development by constructing innovative urban streets, which align with the United Nations' Sustainable Development Goals. Specifically, the social attributes of streets can foster neighborhood communication and improve residents' mental health, contributing to the goal of "good health and well-being". The identification of smart street infrastructure, promotion of hierarchical streets and transportation integration fall within the scope of the goal of "industry, innovation, and infrastructure". Furthermore, the discussion of the synergies between urban streets in terms of livability and mobility, and the proposed recommendations for designing safe street environments, can enhance the construction of "sustainable cities and communities".

In light of the theoretical debate over the identity of streets, i.e., streets as transportation routes or social places? This review posits that streets serve both transportation and social purposes, evolving into places for community, political, economic, and cultural activities. In today's increasingly competitive street space, street efficiency and vitality can be strengthened by developing the synergy of urban mobility and livability instead of enlarging the conflicts. It is worth emphasizing that the social characteristics of streets are frequently expressed through users' behaviors; therefore, studying street-neighborhood relations necessitates an examination of the relationship between users' behavior and street space. In establishing evaluation systems for streets and street users, stakeholders, decision-makers, and participants must be involved in weighting key concerns and indicators to avoid simple additive equations. Moreover, the review highlights the need for streets to be accessible and equitable public spaces for all citizens, particularly considering the needs of elderly and disabled populations in the design process.

Regarding future directions, technological solutions are collaborating to build smart cities. With the emergence of these technologies, IoT devices are becoming increasingly visible on city streets. Through smart street structures, the IoT can transmit real-time traffic information and effectively control street lighting, traffic systems, and automatic navigation systems. These smart devices and analytics can assist with city management and the decision-making process. In terms of research methodology, it can be challenging to establish cause–effect relationships in a cross-sectional approach. Considering the deviation of design ideals from the expected values of the street and the delays brought on by implementation, follow-up, and longitudinal studies will provide more comprehensive insights into the effects of creative design tools. Additionally, streets have multiple identities due to the different types of streets and complex urban context. Further research must expand on the findings of this paper to carefully evaluate different types of streets and specific cultural and geographical environments, in order to provide significant assurance for street design in sustainable urban development.

In conclusion, the innovative street design methods and planning principles have the potential to make a significant contribution to sustainable urban transformation, particularly in terms of enhancing urban mobility and livability. A collaborative effort between urban planning and street space research is essential. This partnership can help to create efficient and livable urban public spaces that meet the diverse needs of urban residents. Predictive street concepts and practices serve as a valuable tool for planners and policy makers in making sustainable policy decisions. By incorporating these concepts, cities can design streets that prioritize the needs of pedestrians and cyclists, while also improving access to public transportation and reducing dependence on private cars. In addition, designing innovative streets requires the incorporation of a range of elements, such as diverse land uses, residential design, highway design, and architectural design. By considering these elements, cities can create environments that promote physical activity, social interaction, and community engagement. Ultimately, by prioritizing the creation of sustainable and livable urban streets and environments, cities can ensure the well-being of their citizens for generations to come.

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Measuring streetscape perceptions from driveways and sidewalks to inform pedestrian-oriented street renewal in Düsseldorf

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A R T I C L E I N F O

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A B S T R A C T

The measurement of urban streetscape quality facilitates the identification of street regeneration. The emerging Street View image and semantic segmentation techniques have recently proven considerable assistance for investigating urban spatial quality. However, current studies using Google Street View (GSV) cannot explicitly reflect pedestrian perceptions, as GSVs are taken from a driveway perspective, which differs significantly from the pedestrian view. This study aims to elucidate the variance in quantitative measurements of streetscape perceptual qualities under different viewpoints and to identify the priority of street renewal based on a combined analysis between street perceptual quality and walking potential. We collected GSVs and self-photographed pedestrian views in the city center of Düsseldorf. 5300 images are gathered, and their semantic information at the pixel level is extracted by the segmentation technique DeepLab V3+. The results indicate that perspective differences have varying geographic effects on street perceptions, with the most significant effect on walkability. In addition, the combined analysis identifies renewal areas and provides planning techniques and operational standards for urban functional zones, streets, and street segments, respectively. The joint spatial syntax and image segmentation-driven approach offers a feasible paradigm for identifying fine-grained street renewal. In short, this study promotes pedestrian-centered urban measurement.

1. Introduction

Urban streets constitute a critical component of the urban public space and are regarded as the primary symbol of the public realm (Appleyard, 1980; Lynch, 1995; Mehta, 2007). There is a growing belief that the urban streets are both mobility channels and social places, illustrating multiple identities. They serve as an extension of the urban environment for many urbanites who use them for social interaction, recreation, commerce, and tourism (Gehl, 2013; Jacobs, 2016). Substantial literature indicates that urban streets with higher pedestrian accessibility have more potential to enhance social engagement and local vitality (Ewing & Cervero, 2010; Gehl, 2013; Mehta, 2007). Over the last few decades, with the design of human-oriented spaces, such as street planning strategic "Link and Place" in Freiberg (Jones et al., 2008) and "bicycle model quarter" in Bremen (Dietz et al., 2019), the urban streetscape in Germany has gradually improved, manifesting in changes to visual appearance, built environment, and spatial perception. The quality of residents' lives and interactions with urban space is intimately related to how they use urban streets and perceive the commuting environment (Cavalcante et al., 2014). To better inform urban regeneration, research on urban street quality and walking accessibility could bridge the gap between spatial measurement and transformation. Therefore, more empirical evidence is needed.

The "Senseable City Lab" at Massachusetts Institute of Technology, the "Beijing City Lab" led by Tsinghua University, and the "Future Cities Lab" at ETH Zürich all employ big data and information technology to better understand how citizens perceive urban space and how to design human-centered public places. In terms of spatial syntax, the University of Edinburgh and University College London have developed "Depthmap" and "Spatial Design Network Analysis" (sDNA) to quantify the topology of urban streets, as well as their centrality, connection, and accessibility. In short, measuring street quality and street access level is becoming increasingly relevant for study in transportation planning, urban spatial studies, civic health, and environmental perception (Beil & Hanes, 2013; Mahmoudi et al., 2015; Zhou et al., 2019). Hence, proposing a high throughput method to quantify residents' visual perceptions of urban streets and analyze the street walking potential helps to gain a better understanding of the role of urban streets and to improve the quality of the urban environment.

So far, researchers have evaluated how individuals visually or

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perceptually perceive the urban environment using questionnaires, face-to-face interviews, and field studies, with Likert scales to measure subjective evaluations. These quantitative research approaches enhanced the measurement of unmeasurable spatial perceptions and documented an abstract view of the urban spatial environment (Ewing & Handy, 2009; McGinn et al., 2007). However, the bias of testers' responses and expectations might lead to inaccurate results (Zhou et al., 2019). Besides, since such audits are time-consuming, they cannot be applied to quantifying large-scale urban environments. Considering these shortcomings, scholars have begun examining the urban environment using automated auditing tools. With the emergence of mapping services and Volunteered Geographic Information (VGI), a vast collection of geotagged images has been assembled and made available to academics, allowing them to study the visual qualities of each street in a city (Zhang et al., 2018). Street-level imagery has facilitated the creation of novel techniques for observing, perceiving, and comprehending the street environment. Spatial features can be extracted in conjunction with image segmentation techniques using computer deep learning and convolutional neural networks. For instance, automatic processing of street view images and satellite images has been analyzed to detect the prevalence and quality of urban greenery (Ye, Richards, et al., 2019). Semantic segmentation and computerized deep learning techniques are employed to assess the correlation between the urban environment with housing prices in Shanghai (Qiu, Li, Zhang, et al., 2021). In short, crowdsourcing map services and geotagged images, as well as semantic segmentation and deep learning techniques, contribute to quantifying the 'unmeasurable qualities' in cities.

Nevertheless, two research gaps remain to be filled in the current studies. The first is the low accuracy of the dataset, e.g., the driveway perspective affects the accuracy of the computational results when studying pedestrian perceptions. Second, virtual audits in large urban areas fail to deliver fine-grained and customized street planning suggestions. Without an in-depth understanding of these two concerns, spatial quality measurement and street network studies cannot improve urban streets to meet residents' mobility and social needs. Hence, we present an algorithmic model based on semantic segmentation combined with an assessment tool based on spatial syntax. The comparative model allows for examining the effect of perspective differences on spatial quality. Metrics include greenness, enclosure, walkability, and imageability, which help evaluate street perceptual quality. By employing sDNA, the assessment tool measures the walking potential of the urban street. The combined analysis facilitates fine-grained spatial identification, street quality assessment, and spatial regeneration.

The primary objective of this study is to quantify the discrepancies between the perspectives of driveway and sidewalk users by comparing Google and self-taken street view images. The findings could offer guidance for the detailed reconstruction of pedestrian-oriented urban streets. To be specific, our study makes three key contributions: (1) to evaluate the walking potential of urban streets through spatial syntax; (2) to quantify streetscape perception and compare differences between driveway and sidewalk perspectives; and (3) to identify the priority of street renewal at different levels and offer fine-grained planning recommendations.

The remainder of this paper is organized as follows. Section 2 reviews the previous approaches and outcomes for assessing street quality and walking potential. Section 3 describes the data and research methodologies. Section 4 summarizes the findings from the virtual audit and field study. In section 5, we discuss the contributions and limitations of this study and draw some conclusions.

2. Literature review

2.1. The key role of urban streets in urban renewal

Streets are an integral part of the built environment, serving as a key determinant of the efficacy of urban renewal efforts (Hassen & Kaufman, 2016). Van Dyck et al. (2013) found that urban streets function as perceived neighborhoods, with street connectivity, density, and access all influencing pedestrian perceptions of safety and social cohesion. De Vries et al. (2013) emphasized the importance of street aesthetics and upkeep, including graffiti, landscaping, street shadows, and street amenities, in promoting urban renewal and neighborhood interactions. Specific street features such as plants, as noted by Burrage (2011), can help create green and livable cities. De Vries et al. (2013) hypothesized that high-quality streetscape greenery can enhance urban vitality and social cohesion by providing more public social spaces. Green spaces can serve as recreational areas for youth and children (Burrage, 2011). The density of urban streets and the number of intersections play a crucial role in determining street connectivity, with efficient street connections and public transportation systems enhancing mobility efficiency and social participation (Lehning, 2014). Moreover, the walkability of streets is closely linked to urban design goals, with a large body of literature indicating that walkable cities can promote resident health (Lynch, 1964; Mehta, 2008).

The United Nations has established Sustainable Development Goals (SDGs) to drive sustainable urban renewal. One of the key objectives is to achieve "good health and well-being," which can be facilitated by efficient street networks and high-quality street spaces that provide quick access to urban facilities. Improving the accessibility and density of street infrastructure promote resilient, inclusive and sustainable urban infrastructure. In addition, "sustainable urban communities" can be built through increased street greening and safety, thereby enhancing the vitality of urban communities.

In comparison to rapidly urbanizing cities in the global South, Western European cities prioritize precise urban renewal and transformation in their street planning initiatives, with the ultimate goal of promoting urban revitalization (Couch et al., 2011). Large-scale, high-precision spatial quality measurements have therefore become a top priority in the field of street research. Utilizing fine-grained measurement methods to evaluate street spatial quality will provide theoretical recommendations for urban planning departments seeking to adopt targeted street reconstruction, further contributing to the sustainable development of cities.

2.2. Application of SVI and semantic segmentation

Street View Image (SVI) has played an increasingly essential role in urban research in recent years. Research can acquire street images by crowdsourcing map services, which significantly increases the ease of access to urban spatial awareness data (Qiu, Li, Liu, & Huang, 2021). SVI incorporates street view images from providers such as Google, Baidu, and Tencent, making it a suitable source of datasets for high-throughput studies. At an early stage, SVI services were recognized for their superior performance in appraising the built environment (Kelly et al., 2013). Since 2013, SVI has been used to investigate a variety of characteristics of the urban environment, including property value (Qiu, Li, Zhang, et al., 2021), crime rate (McKee et al., 2017), urban infrastructure (Abou Chacra et al., 2016), and green spaces (Ye, Richards, et al., 2019).

Advancements in deep learning and computer vision techniques have enabled the processing of massive amounts of data and improved the efficiency of spatial analysis (Biljecki & Ito, 2021). Earlier semantic segmentation algorithms categorized components primarily based on pixel color, which results in misclassification (failing to distinguish graffiti or mistake all the green pixels as vegetation). The development of new neural network topologies, such as Segnet, Segformer, and Deeplab V1-3+, has enhanced the performance of image detection (Ma et al., 2021). In addition, urban studies apply pre-trained datasets such as Cityscapes and ADE20K to create fine-grained urban-aware maps across geographic regions. The Cityscapes dataset has 30 classes grouped into eight categories, whereas the ADE20K dataset contains 150 semantic categories, including sky, road, grass, and discrete objects like person, car, and bed. Hence, the ADE20K dataset and Deeplab V3+

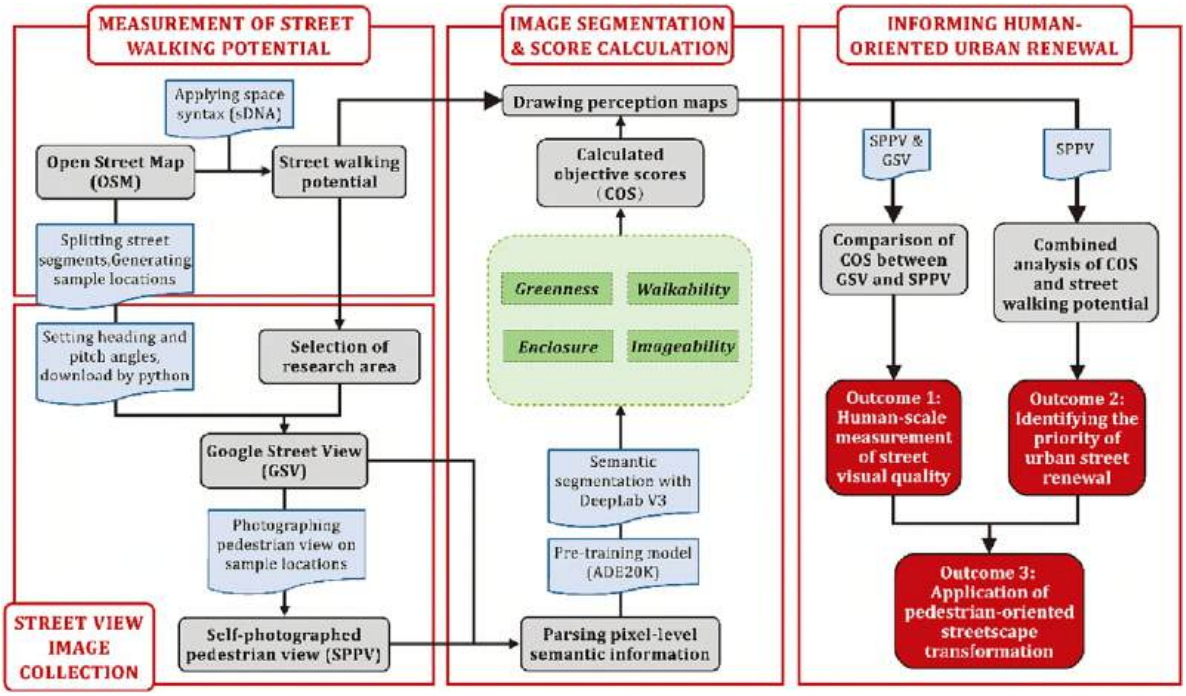


Fig. 1. Analytical framework.

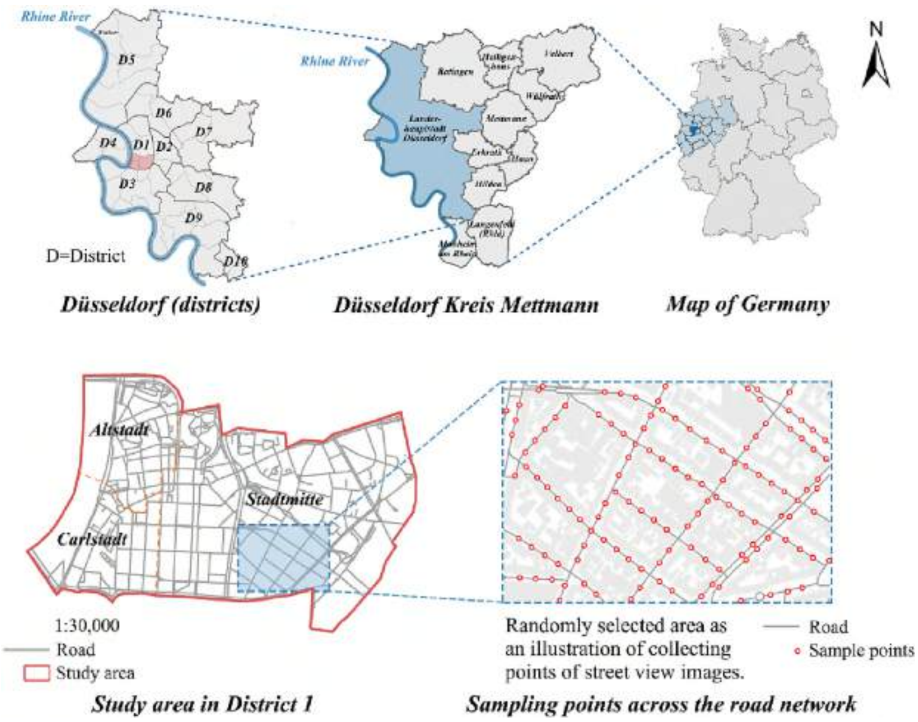


Fig. 2. Selection of study area.

based on Deep Convolutional Neural Networks (DCNNs) are chosen to complete image segmentation.

2.2.1. *Perceptual assessment of urban streets*

Sense of place is an essential component of a place (Hubbard & Kitchin, 2010) and refers primarily to the human experiences and

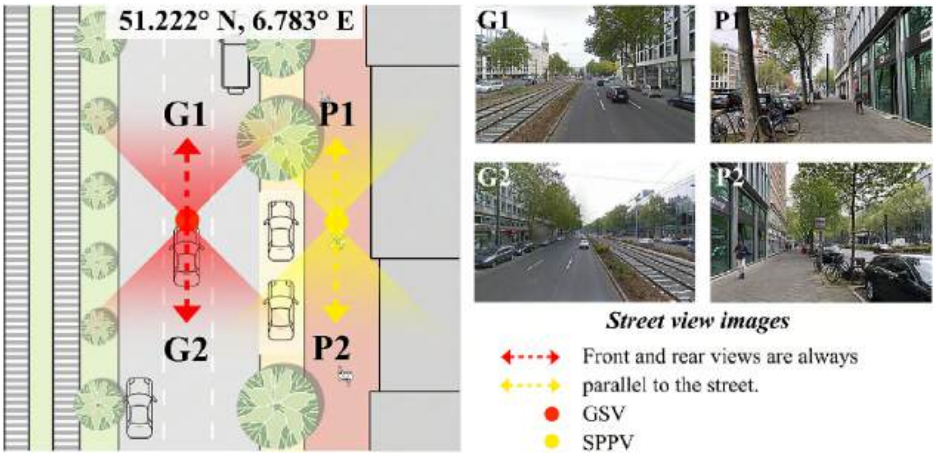


Fig. 3. Collection of street view images.

ambiguous meanings associated with the place (Cresswell, 2014). Environmental psychology research defines *environmental perception* as an emotional attachment to a particular environment through physical environmental features, cognition, meaning, and place attachment, where individuals have a propensity to remain and feel comfortable and safe (Rollero & De Piccoli, 2010). The perception of urban streets substantially impacts individuals' impressions of a place, sociability, physical activity, travel patterns, and willingness to stay (Ewing & Cervero, 2010; Gehl, 2013). There is a basic consensus among scholars that urban street perception has a beneficial effect on human health.

Street perception is divided into subjective and objective measures. The term "subjective measurements" refers to evaluation scores derived from a survey that reveal subtle correlations (Lin & Moudon, 2010). Small-scale data and low-throughput quantitative research methods have been commonly used in subjective measurements, including surveys, interviews, and questionnaires to capture users' attitudes. Using these methodologies, Gehl (2013)'s research on civic life and street spaces has advanced the understanding of human social interactions. Ewing et al. (2006) rated the urban design quality of streetscapes by a panel of experts through 205 street videos and selected five indicators (imageability, enclosure, human scale, transparency, complexity) from a list of 41 assessment metrics. The final operational definition and measurement protocol for urban street design quality was developed based on statistical relationships. With the improvement of SVI and computer deep learning techniques, Zhang et al. (2018) predicted subjective perceptions of urban environments, including safe, lively, boring, wealthy, depressing, and beautiful. They analyzed the correlations between urban heterogeneity and function. By choosing the same criteria and scoring mechanism, Wang et al. (2019) examined the linkage between neighborhood and physical activity in Guangzhou. Moreover, datasets such as "Place Pulse 1.0", "Place Pulse 2.0", and "Streetscore" are widely used to assess street safety, visual signals, aesthetics, and social equity (Naik et al., 2014; Quercia et al., 2014; Salesses et al., 2013).

Likewise, objective measurement of the street environment is based on the development of SVI, VGI, and deep learning. Objective metrics include greenness, openness, imageability, enclosure, walkability, and street canyon morphology. Transparency occasionally appears among the objective metrics, depending on whether the analysis software selected by the researcher is able to identify the window elements of the street façade (McGinn et al., 2007). Among these metrics, street greenery is the most frequently measured visual element. Objective metrics are typically assessed to quantify urban greenery and evaluate the visibility of urban forests are the Green View Index (GVI), the temporal changes in GVI (Li, 2021), the distance to urban greenery combined with remote sensing images (Barbierato et al., 2020; Richards & Wang, 2020), or the personal exposure to urban greenery (Zhang et al., 2021). Qiu, Li, Zhang, et al. (2021) selected six indicators (greenness, walkability, safety, imageability, enclosure, and complexity) and investigated the coherence and divergence in ML-predicted subjective scores and formula-derived objective scores, and compared their effects in affecting house prices taking Shanghai as a case study. Ma et al. (2021) used eye-level perception of the street canyon to compare the differences between objective and subjective evaluations, and discussed the variations of the perception outcomes across different function streets, and analyzed the net effect of urban renewal projects (URPs) on streetscape transformation.

In short, scholars have compared the differences in results between subjective and objective measures and have begun to choose objective measurement approach as the primary method of study, owing to the advantage that objective measurements can transform perception results into design recommendations that can be employed to guide street intervention (Qiu, Li, Zhang, et al., 2021).

2.3. Measurement of street walking potential

The walking potential of urban streets represents the willingness of individuals to engage in specific activities in particular locations, such as living, working, shopping, socializing, and recreating (Xiao et al., 2017). Highly walkable streets and accessible networks could make it more efficient and easier to walk or bicycle from one place to another. Several studies have demonstrated that inhabitants living in neighborhoods with highly walkable streets have higher active transportation levels (Owen et al., 2004; Saelens et al., 2003).

The topological properties and spatial distribution of urban streets can determine the walking potential and accessibility of urban street networks. The spatial syntax is a research methodology developed by University College London in the early 1980s that focuses on the role of spatial networks in shaping social and transportation patterns. The spatial syntax is used to quantify urban spaces, particularly streets, for human activity and spatial perception by establishing topological relationships between points and lines. On this basis, the Urban Network Analysis Toolbox (UNA), Depthmap, Place Syntax Tool (PST), and Spatial Design Network Analysis (sDNA) have been developed to provide technical support for the walking potential of streets, urban mobility, and travel patterns.

sDNA serves as a plug-in for ArcGIS, enabling the examination of centrality and network detours (Cooper, 2019). It computes measures of accessibility (reach, mean distance/closeness centrality, gravity), flows (bidirectional betweenness centrality), and efficiency (circuity), as well

Table 1
Formulas and explanations for scores of indices.

Indices	Qualitative definition	Formula	Explanation
Greenness	Greenness represents green landscape elements such as grass, trees, vegetation, and green belts, intended to raise active awareness of the distribution of vegetation on streets (Ma et al., 2021).	$G_i = \frac{\sum_{i=1}^{2} GP_i}{\sum_{i=1}^{2} P_i}$	GP_i denotes the proportion of green pixels, including plant, tree and grass; P_i is the total number of pixels in image *i*.
Enclosure	Enclosure represents the degree of human scale. The percentage of vertical elements to the overall pixel (sky excluded) is measured to express enclosure (Ewing & Handy, 2009; Rapoport, 2016).	$E_i = \frac{\sum_{i=1}^{2} (B_i + T_i + W_i + F_i)}{\sum_{i=2}^{2} (1 - S_i)}$	B_i denotes the proportion of building pixels, T_i denotes the proportion of tree pixels, W_i denotes the proportion of wall pixels, R_i denotes the proportion of road pixels, and $P1_i$ denotes the proportion of sidewalk pixels. F_i denotes the proportion of fence pixels.
Walkability	Walkability measures the support of the outdoor environment for walking (Ewing & Handy, 2009), given here as the ratio of sidewalk to the driveway.	$W_i = \frac{\sum_{i=1}^{2} P1_i}{\sum_{i=1}^{2} (R_i + P1_i)}$	
Imageability	Imageability responds to the richness of the built environment and street furniture, with objective elements including signboard, sculpture, person, and bench (Ma et al., 2021).	$I_i = \frac{1}{2}\sum_{i=1}^{2} (S_i + S1_i + B_i + P2_i + B1_i)$	S_i denotes the proportion of signboard pixels, $S1_i$ denotes the proportion of sculpture pixels, $P2_i$ denotes the proportion of person pixels, $B1_i$ denotes the proportion of bench pixels.

as convex hull properties. To date, the research using sDNA has mainly explored the relationship between street walking potential and urban public facilities (Huang et al., 2020), with some focus on residents' health (Sarkar, 2013), travel mode choice (Liu et al., 2017), and spatial equity (Li et al., 2021; Ma, 2020). However, studies failed to link street walking potential to spatial perceptions. The limited evidence quantifies the contribution of street visual greenery to the value of street walkability from a human-centered perspective (Ye, Richards, et al., 2019). However, it cannot reflect the performance of other perceptual aspects.

3. Data and methodology

3.1. Research framework

This study contains four main phases (Fig. 1). Street walking potential measurement, street view image collection, image segmentation, score calculation, and informing human-oriented urban renewal. Specifically, Open Street Map (OSM) was used to get information on the street network in Düsseldorf, Germany. This is followed by a regional study and categorization the street walking potential through sDNA. Second, Google Street View (GSV) images were acquired from Google Maps via Python, and self-photographed pedestrian views (SPPVs) were collected at the same coordinates for the comparative study. Third, we extracted elements from the streetscape images using DeepLab V3+ and the corresponding ADE20K pre-trained scene resolution dataset to achieve image segmentation. Metrics for street visual perception are then calculated based on the optimized formulas. After that, the variations in street perception were examined between the GSV and SPPV datasets to support human-scale street measurement. The combined analysis of street walking potential and street perceptual quality was carried out to identify the priority of the urban renewal area. Finally, pedestrian-oriented streetscape transformation and planning recommendations were made.

3.2. Study area and data collection

We chose Düsseldorf as the site for investigation. Düsseldorf has an area of 217.41 km^2 and a population of 570,000. It was ranked 6th as a livable city in Europe in the Mercer Quality of Living Survey in 2019. We chose roads with vehicle travel speed below 50 km/h because speed above 50 km/h has no pedestrian lanes and is not in the measurable range. Then we conducted a walking potential analysis of the entire city. The results of walking potential will be illustrated in Section 4.1, and the mechanics of sDNA are described in the supplementary material. We chose Altstadt (0.5 km^2), Carlstadt (0.46 km^2), and Stadtmitte (1.72 km^2) in district 1 for the field study (Fig. 2). The process and reasons for specific site selection are described in detail in Section 4.1. The zoning data was downloaded from the official website (https://www.duesseldorf.de/geoportal.html).

We programmed the acquisition of GSVs every 30 m to achieve a comprehensive representation of the street visualization in the study area (Fig. 2). A total of 1604 sampling points were generated. The collection began in March 2022, and 1325 sampling points remained after filtering the acquired street scenes by excluding invalid images (Appendix I).

The GSVs were requested in an HTTP URL using the Google Maps API. By defining the URL parameters sent through a standard HTTP request using the Google Maps API, users can obtain a static image from any direction and viewing angle for any point where GSVs are available. A common shortcoming in current research is the use of true north (0°), true south (180°), true east (90°), and true west (270°) as the heading angles for acquiring street view images, which struggles to simulate the pedestrians' view due to the crisscrossing of the street network. We acquired front and rear street view images that were parallel to the street at each point. We developed a Python script to analyze the geographic characteristics of the street and calculate the heading view angle at sampled points. As shown in Fig. 3, a front and rear street view image parallel to the street was acquired at each point. Each image was 640 × 400 pixels in size. We set the horizontal field of view to 90° and the vertical view angle to 0° to approximate residents' perceptions (Li et al., 2015). Our selection of the front and rear perspectives of SVI was principally underpinned by three considerations. Firstly, it was informed

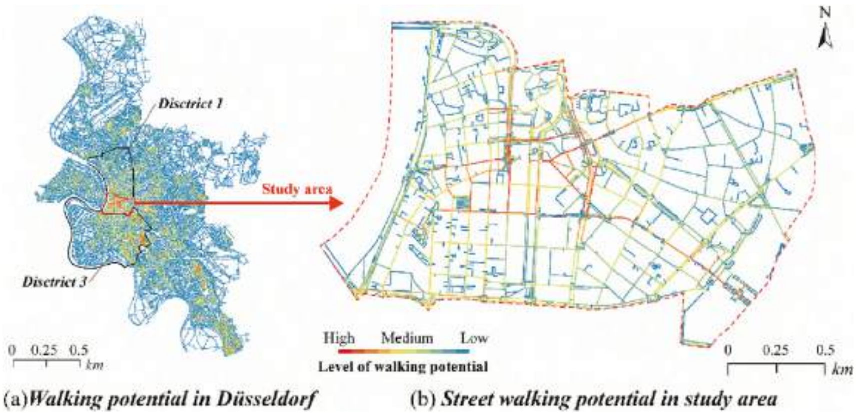


Fig. 4. Street walking potential in Düsseldorf and study area.

Table 2
Statistics of the segmented results from GSV and SPPV (%).

Indicators	Visual elements	Max		Min		Mean		S.D.	
		GSV	SPPV	GSV	SPPV	GSV	SPPV	GSV	SPPV
Initial elements from ADE20K	Wall	0.2203	0.4943	0	0	0.0051	0.0089	0.0179	0.0306
	Building	0.7248	0.7656	0	0	0.2920	0.3797	0.1566	0.1865
	Sky	0.4739	0.6056	0.533	0	0.1339	0.1163	0.0842	0.1021
	Tree	0.5511	0.6383	0	0	0.1329	0.1491	0.1153	0.1393
	Road	0.4955	0.3123	0	0	0.2328	0.0613	0.1024	0.0557
	Grass	0.5123	0.3819	0	0	0.0201	0.0132	0.0540	0.0349
	Sidewalk	0.4624	0.3137	0	0	0.0822	0.1271	0.0919	0.0641
	Person	0.3512	0.1707	0	0	0.0055	0.0145	0.0193	0.0225
	Plant	0.2423	0.2653	0	0	0.0085	0.0144	0.0190	0.0337
	Car	0.2352	0.2140	0	0	0.0442	0.0433	0.0438	0.0509
	Fence	0.3479	0.1443	0	0	0.0074	0.0070	0.0207	0.0165
	Signboard	0.1088	0.0929	0	0	0.0047	0.0121	0.0081	0.0148
	Bench	0.0289	0.0580	0	0	0.0004	0.0007	0.0024	0.0031
	Sculpture	0.0552	0.0135	0	0	0.0001	0.0001	0.0019	0.0008
Perceptual indices	Greenness	1	0.846	0	0	0.178	0.183	0.165	0.171
	Enclosure	1	1	0	0.261	0.612	0.650	0.132	0.103
	Walkability	1	1	0	0	0.261	0.704	0.258	0.217
	Imageability	1	1	0	0.001	0.414	0.567	0.216	0.211

by the study conducted by Kim et al. (2021), which discovered considerable differences of street elements in the GSV-based measurements between the left and right orientations. Contrarily, the front and rear images tended to exhibit greater uniformity. The left or right views, particularly of sidewalks, exhibiting negative correlation values. Asymmetry and negative correlation of left and right views could potentially reduce the comparability of the study, thus affecting the stability of resultant outcomes. Secondly, we drew upon environmental psychology (Bargh et al., 1996), which identified that the behavior of local residents tends to remain relatively unchanged in daily life. Generally, their visual trajectory tends to align with the street structures. Hence, we concentrated our perspective on the front-rear continuum of the street layout (Ye, Richards, et al., 2019). Thirdly, we referenced a study by Ye, Zeng, et al. (2019), which examined visual measurements of streets. Their work corroborated the validity and reliability of using front and rear perspectives to measure the visual quality of streetscapes.

In total, 2650 GSVs were received to reflect the visual experiences of the urban streets. In addition to virtual audits, field measurements were conducted to provide a self-collected dataset with higher accuracy. Through recording the location of sampling points, self-photographed pedestrian views (SPPVs) were taken next to the driveway. Except for setting the height of the perspective at 1.7 m to simulate a human viewpoint, other settings were identical to GSVs. To exclude the influence of climate, 2650 SPPVs were taken on clear days between April 25 and May 2, 2022, from 10 a.m. to 5 p.m. The average temperature is 23°. The utilization of "self-photographed pedestrian views" does not pose any ethical or data privacy concerns since we obscure all sensitive information, such as faces and license plates, during the data collection process.

3.3. Selection of the four perceptual indices

The visual-perceptual quality of streets benefits urban health and social cohesion, which is therefore seen as a significant factor in determining how urban residents choose to travel and commute. Urban streets with high visual quality and walking potential increase the efficiency of urban transport while contributing to economic growth. Inspired by the protocol for measuring street walkability (Ewing et al., 2013), we selected four indices to better inform scene-understanding practices (Ma et al., 2021): greenness, enclosure, walkability, and imageability. Transparency and complexity were emphasized in Ewing's study (Ewing et al., 2013). However, transparency was excluded because Deeplab V3+ could not identify the glass on the building façade. Due to the multiple covariances between complexity and imageability, complexity was also excluded. The definitions of selected indices are explained in Table 1.

Building upon the study of Ma et al. (2021), our formula incorporates several improvements to enhance its accuracy and validity. Our

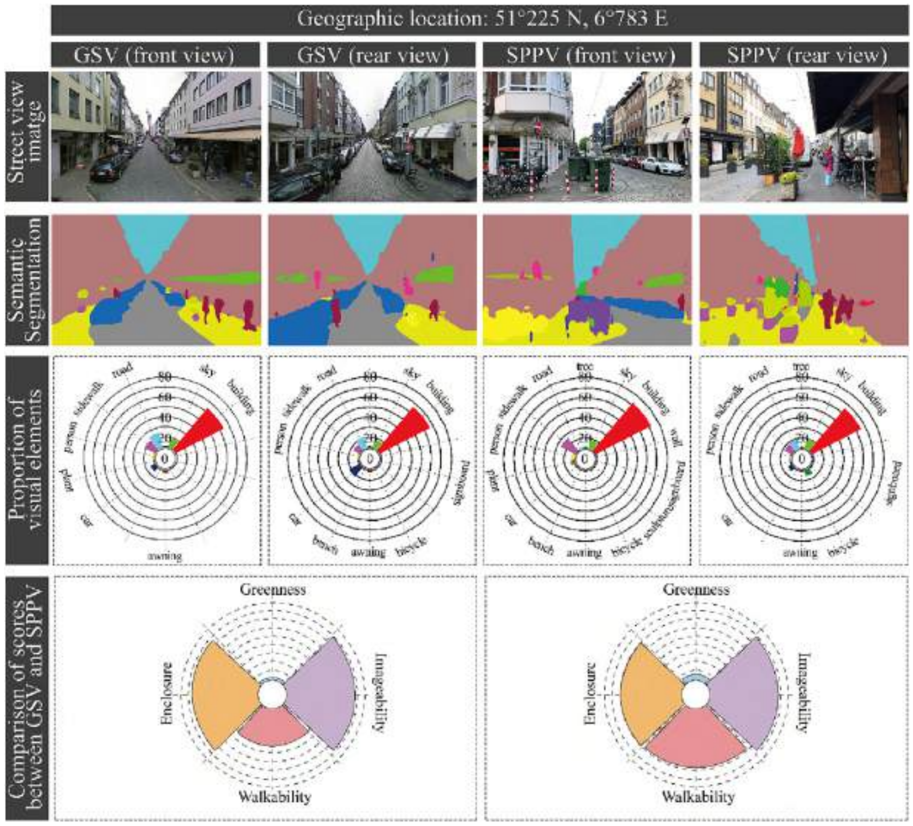


Fig. 5. Classified visual elements and perceptual scores of the same coordinates from different viewpoints.

revisions primarily include the following: (1) We excluded the variable ‘openness’ as it is not proposed by Ewing and Handy (2009) and overlaps with the concept of ‘enclosure,’ which can lead to multicollinearity issues; (2) We expanded the definition of ‘greenness’ to encompass plants and grass, which are integral components of street greenery; (3) We redefined ‘enclosure’ based on Ewing’s definition as the degree to which buildings, walls, trees, and other vertical elements visually define streets and public spaces. Our revised formula captures all necessary elements, including walls and fences in the numerator, and the total pixel area excluding the sky element in the denominator, based on “proportion sky across,” as per Ewing’s significant physical features of enclosure; (4) The existing formula for calculating walkability that includes fence in the numerator is not well founded. Using only the road as the denominator neglects the vital role of sidewalks in walking. Therefore, we adopted the ratio of sidewalk area to the total area of lanes and walkways as the foundation for measuring walkability; (5) We enriched the calculation of imageability by integrating pixels of people, benches, and sculptures. This addition enhances the significance of urban landmarks and street symbols, thus better reflecting the diversity and richness of the surrounding environment.

4. Results

4.1. Analysis of street walking potential based on space syntax

Fig. 4 illustrates the street walking potential for the city of Düsseldorf and the study area. Streets with high, medium, and low walking potential are shown in red, yellow, and blue, respectively. From Fig. 4a, the southern part of district 1 and the eastern part of district 3 have more diverse pedestrian potential. Considering the fieldwork, we narrowed the study area to the southern part of district 1, namely, Altstadt, Carlstadt, and Stadtmitte. There is a distinct trend of decreasing walking potential from the city center to the suburbs (Fig. 4b). The streets with high potential consist mainly of pedestrianized commercial streets and major avenues, including Steinstraße, Königsallee, and Blumenstraße.

4.2. Descriptive statistics of the segmented results between GSV and SPPV

The pixel-level segmentation of street images was implemented by DeepLab V3+, and 14 classes of visual elements were selected for calculation; the extrema and standard deviation are summarized in The building, sky, and trees dominate the image and are the primary source of pedestrian impressions of the street; they determine the greenness and enclosure. The proportion of buildings and trees in SPPV is slightly higher than in GSV due to the proximity of the buildings and greenery. The mean values of the sidewalk (0.13) and road (0.06) in SPPV and sidewalk (0.08) and road (0.23) in GSV can be categorized as medium-scale visual elements. In contrast to the driveway, the proportion of sidewalk pixels in SPPV is significantly higher than in GSV due to perspective differences. Although the driveway and sidewalk pixels are less dominant than the sky, trees, and buildings, other street elements, including plants, cars, signboards, benches, and sculptures, are based on them, and they are the most dynamic aspect of the street, influencing pedestrian behavior.

In Table 2, the building, sky, and trees dominate the image and are the primary source of pedestrian impressions of the street; they determine the greenness and enclosure. The proportion of buildings and trees in SPPV is slightly higher than in GSV due to the proximity of the buildings and greenery. The mean values of the sidewalk (0.13) and road (0.06) in SPPV and sidewalk (0.08) and road (0.23) in GSV can be

Table 3
Correlation matrices of the visual elements and calculated indices.

Part A: correlation coefficients of four indices from GSV dataset

Indices	Greenness	Enclosure	Walkability	Imageability
Greenness	1	−0.169**	−0.139**	−0.793**
Enclosure	(−0.250**)	1	0.002*	0.663**
Walkability	(0.011)	(0.134**)	1	0.140**
Imageability	(−0.835**)	(0.641**)	(0.079**)	1

Part B: correlation coefficients of enclosure and its visual elements from GSV dataset

Elements	Enclosure	Building	Tree	Wall	Fence	Sky
Enclosure	1	0.662**	0.022	−0.045	0.060*	−0.797**
Building	(0.654**)	1	−0.685**	−0.194**	−0.082**	−0.525**
Tree	(−0.025)	(−0.716**)	1	0.015	−0.083**	−0.181**
Wall	(−0.059*)	(−0.146**)	(−0.081**)	1	0.058*	0.157**
Fence	(0.029)	(−0.221**)	(0.148**)	(0.013)	1	0.166**
Sky	(−0.693**)	(−0.446**)	(−0.186**)	(0.048)	(0.118**)	1

Part C: correlation coefficients of walkability and its visual elements from GSV dataset

Elements	Walkability	Sidewalk	Road
Walkability	1	0.891**	−0.803**
Sidewalk	(0.619**)	1	−0.626**
Road	(−0.783**)	(−0.267**)	1

Part D: correlation coefficients of imageability and its visual elements from GSV dataset

Elements	Imageability	Building	Sculpture	Signboard	Bench	Person
Imageability	1	0.991**	0.004	0.010	−0.045	0.152**
Building	(0.990**)	1	−0.016	−0.035	−0.067*	0.031
Sculpture	(−0.010)	(−0.014)	1	−0.026	0.136**	0.061*
Signboard	(0.182**)	(0.107**)	(−0.026)	1	−0.046	−0.040
Bench	(−0.044)	(−0.067*)	(0.035)	(−0.050)	1	0.057*
Person	(0.079**)	(−0.041)	(0.000)	(−0.014)	(0.081**)	1

Note: Data with brackets are from SPPV dataset, data without bracket are from GSV dataset.
* $p < .05$.
** $p < .01$.

categorized as medium-scale visual elements. In contrast to the driveway, the proportion of sidewalk pixels in SPPV is significantly higher than in GSV due to perspective differences. Although the driveway and sidewalk pixels are less dominant than the sky, trees, and buildings, other street elements, including plants, cars, signboards, benches, and sculptures, are based on them, and they are the most dynamic aspect of the street, influencing pedestrian behavior.

We randomly selected data from one sampling point, and the obtained semantic segmentation results with the calculated perception scores are displayed in Fig. 5. It illustrates image data for the same geographical location taken from both driveway and pedestrian views. The pie chart demonstrates pixel-level elemental information; values increase by 10 % from the inside out. On the left are the front and rear view of the Google Street View, and on the right are views from sidewalk. As can be seen, there is no significant difference in the quantity and proportion of dominant visual elements in the images acquired at the same sampling points. The values for buildings and sky are close, which leads to similar scores for enclosure, and imageability. However, the images from SPPV show a more significant proportion of the sidewalk, which impacts the calculation of walkability. The walkability from SPPV is 0.710, more than double that of GSV (0.317). Data from a randomly selected sampling point does not adequately represent the overall quality of streets and the variation from different viewpoints.

4.3. Correlation analysis with initial elements between GSV and SPPV

Pearson correlation analysis was applied to validate the multicollinearity of the scores of 1350 sampling points in GSV and SPPV. The pairwise comparison matrix of the correlation coefficients based on the bilateral significance test is given in Table 3. Part A demonstrates that 90 % of the data exhibit substantial association. Greenness has negative correlations with enclosure and imageability, whereas enclosure has positive correlations with walkability and imageability. The findings are consistent with the previous studies (Ma et al., 2021). Furthermore, the correlations between GSV and SPPV are comparable, except for the correlation between greenness and walkability.

The bivariate correlation coefficients for the enclosure, walkability, and imageability for their corresponding visual elements (Part B to Part D). Greenness was no longer analyzed because it wasgenerated by a single visual element. In Part B, GSV and SPPV show identical results in the correlation analysis regarding enclosure. Specifically, there is a significant positive correlation between architecture and enclosure, with a correlation coefficient of 0.6. Likewise, there is a negative association between sky and enclosure, with the correlation coefficient ranging from −0.7 to −0.8. This indicates that enclosure decreases as the exposure to the sky increases. Moreover, sidewalk and walkability have correlation values of at least 0.6, indicating a positive correlation, and roads and vice versa (Part C). There is a strong positive correlation of 0.99 between building and imageability, while the association between imageability and other elements (sculpture, signboard, bench, and person) is poor. Nevertheless, the correlation coefficients between these elements are less than 0.15, which indicates that they are relatively independent of each other. It helps reduce multicollinearity, which is appropriate for measuring the quality of streets.

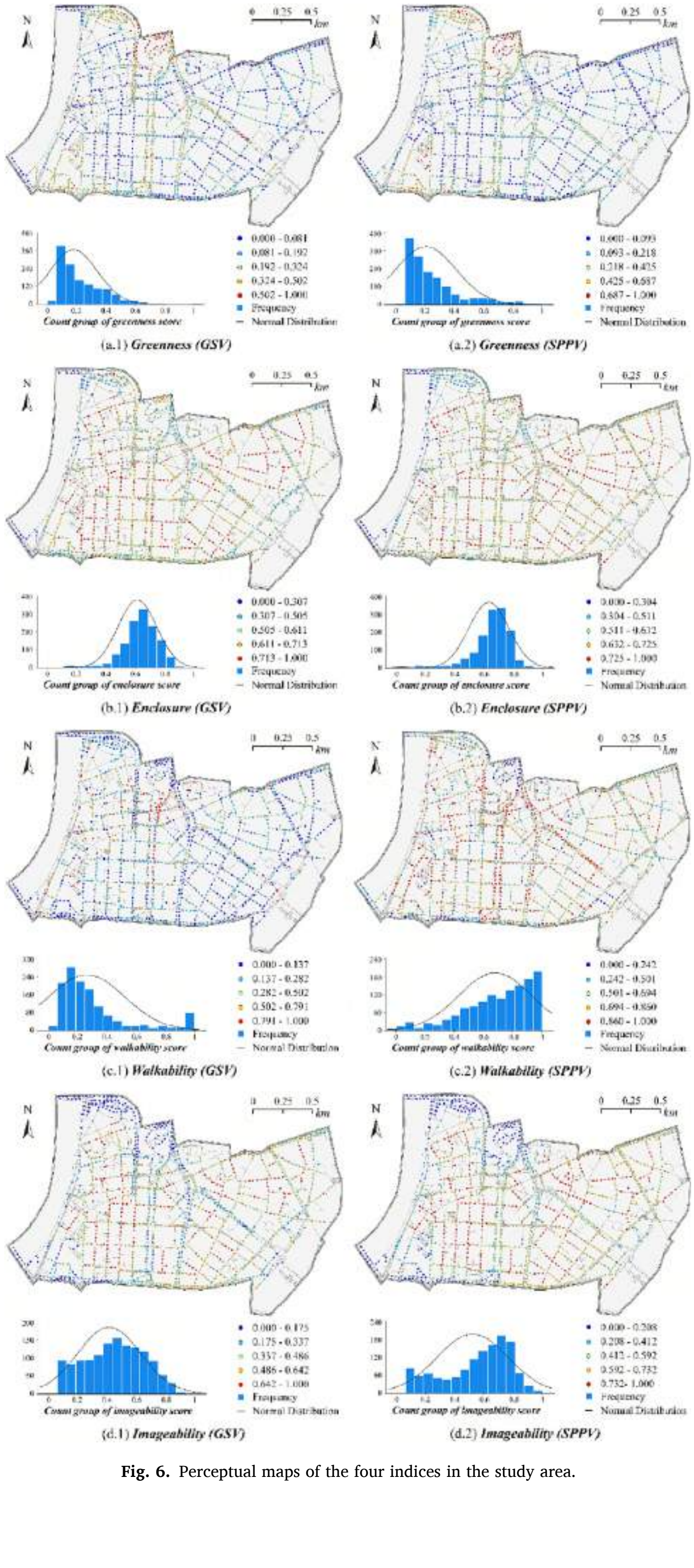


Fig. 6. Perceptual maps of the four indices in the study area.

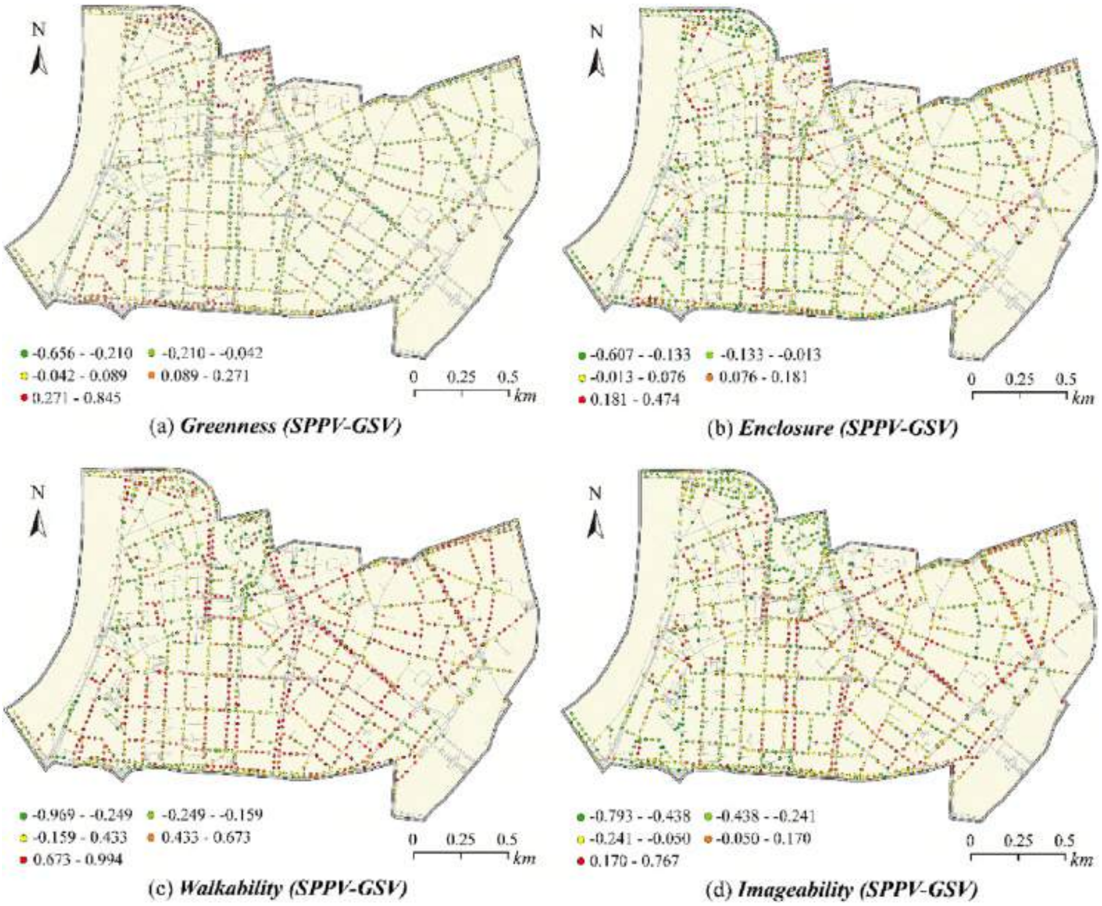


Fig. 7. Difference analysis of the four street indices.

Fig. 8. Street walking potential and overall quality scores.

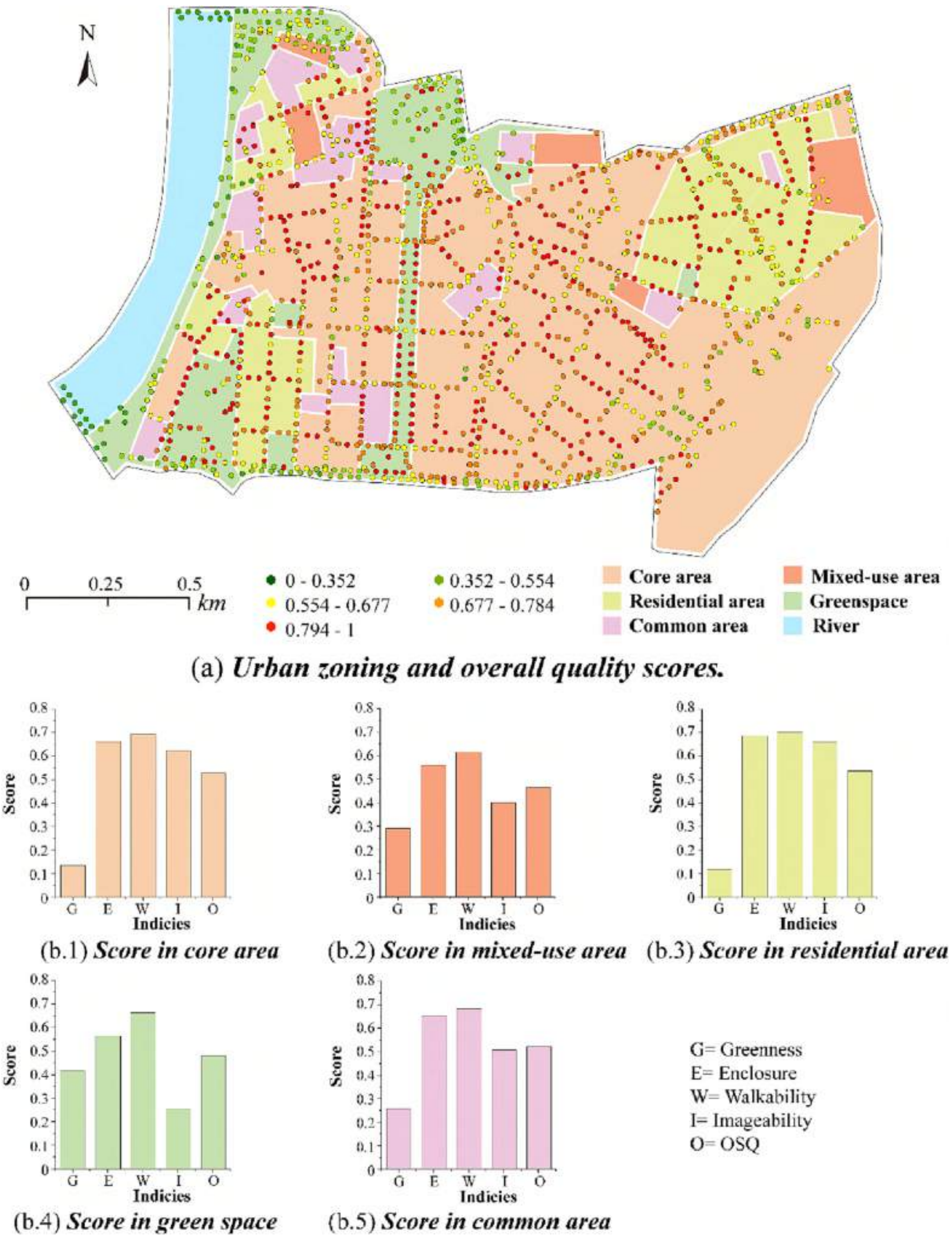


Fig. 9. Comparasion of perceptual scores in different urban functional areas.

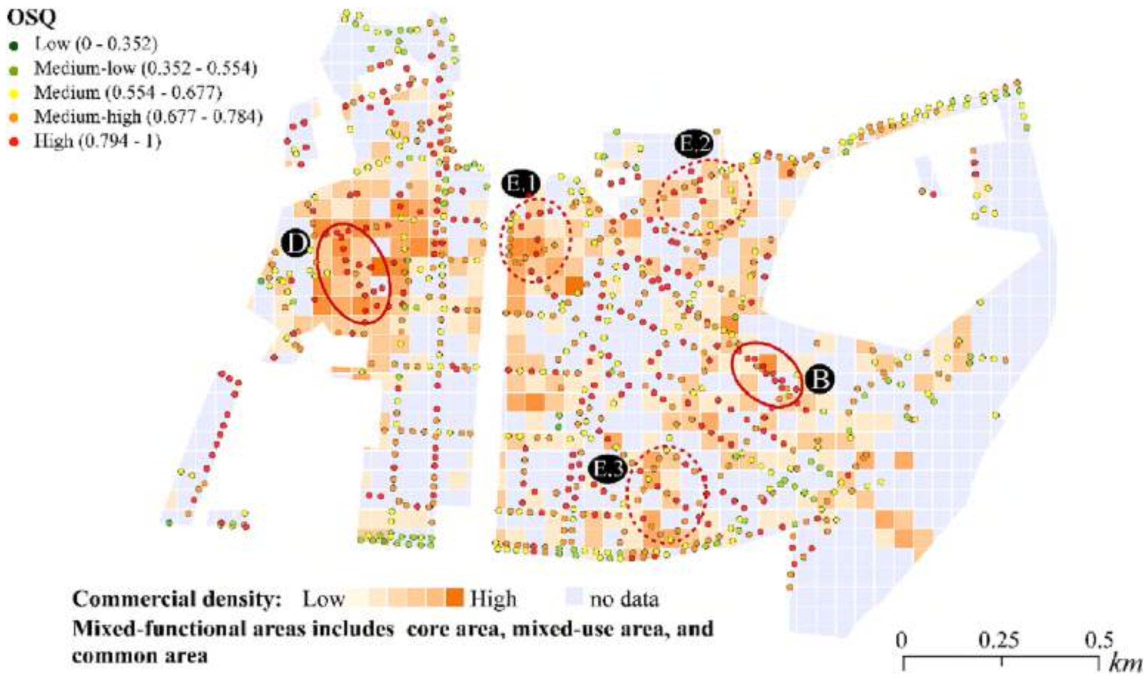


Fig. 10. Commercial density in mixed-functional areas and OSQ.

4.4. Spatial patterns of visual perceptual variables

Fig. 6a demonstrates that, except for green spaces where high greenness scores are clustered, greenness is generally low and exhibits a mild tendency of deterioration from the main streets to the periphery. Compared to GSV, greenness from SPPV is lower on the main streets in the city center, probably because the vehicular viewpoint can observe street trees on both sides, whereas the sidewalk only has exposure to one side. Both GSV and SPPV exhibit large areas with high enclosure scores due to the enclosure of buildings, trees and exposure to the sky. In Fig. 6c, the scores for walkability indicate the most noticeable difference in results due to different viewpoints. The GSV data indicates that, except for the main streets in the city center, all other districts are in the significantly lower range. However, the SPPV results show that most urban centers have high walkability scores and gradually decline from the center to the suburbs. The results are biased because the driveway perspectives cannot reflect walkability from a pedestrian perspective. Finally, GSV and SPPV indicate that imageability scores are generally high and widely distributed in residential areas and small-scale commercial streets (Fig. 5d).

4.5. Differences of spatial patterns in perceptual scores between GSV and SPPV

The difference in indices between the sidewalk and the driveway perspective was obtained by subtracting each score of GSV from SPPV. The results are shown in Fig. 7. In Fig. 7a, the greenness obtained from SPPV shows a lower score in the main street compared to GSV because wider streets allow pedestrians only exposure to one side of the street trees. Greenness has a higher score in the suburban and northern areas in SPPV due to the proximity to the park and meadow. 43 % of sampling points in SPPV show a lower score in the enclosure than GSV. These are mainly located on secondary streets (Fig. 7b). The most noticeable variation in viewpoints is the results of street walkability. 88 % of the sampling points have considerable better walkability in SPPV than GSV, evenly distributed throughout the whole study area, especially along the main streets (Fig. 7c). Compared to Fig. 6d, Fig. 7d reveals that imageability scores are much higher in the main streets in SPPV than GSV, and significantly lower on secondary streets.

4.6. Combined analysis between street walking potential and overall street quality

Separate perceptual scores might reflect the quality of urban streets in different dimensions; however, accessing the overall spatial quality of streets is challenging. Based on the results above, we developed a calculation of the overall street quality. We found that greenness, enclosure, walkability, and imageability positively correlate with street visual quality. Therefore, we assign a weight of 25 % to each of these four indices. The formula is as follows, where O_{sq} denotes overall street quality (OSQ). All indicator data were normalized. This formula is used in all of the overall street quality results below:

$$O_{sq} = G_i \times 0.25 + E_i \times 0.25 + W_i \times 0.25 + I_i \times 0.25$$

We normalized the OSQ and divided them into five intervals using the natural discontinuity method, from green to red as low, medium low, medium, medium high, and high, respectively. In Fig. 8, the sampling points with high scores are mainly concentrated on the main streets in the center and exhibit a gradual decline to the edge. We found a continuity in street quality, i.e., the same street presents similar scores, supporting the identification of street-based regeneration in the following sections. The combined analysis demonstrates that the street quality does not entirely correspond with walking potential. Area A shows a high walking potential but a medium street quality. These street segments could be effectively identified and given a higher priority for upgrading. However, Area B and C indicate a high spatial quality with low walking potential. This can be affected by several variables, including road width, the function of the urban area, and commercial density. The disparity between walking potential and street quality offers a database for fine-grained urban renewal.

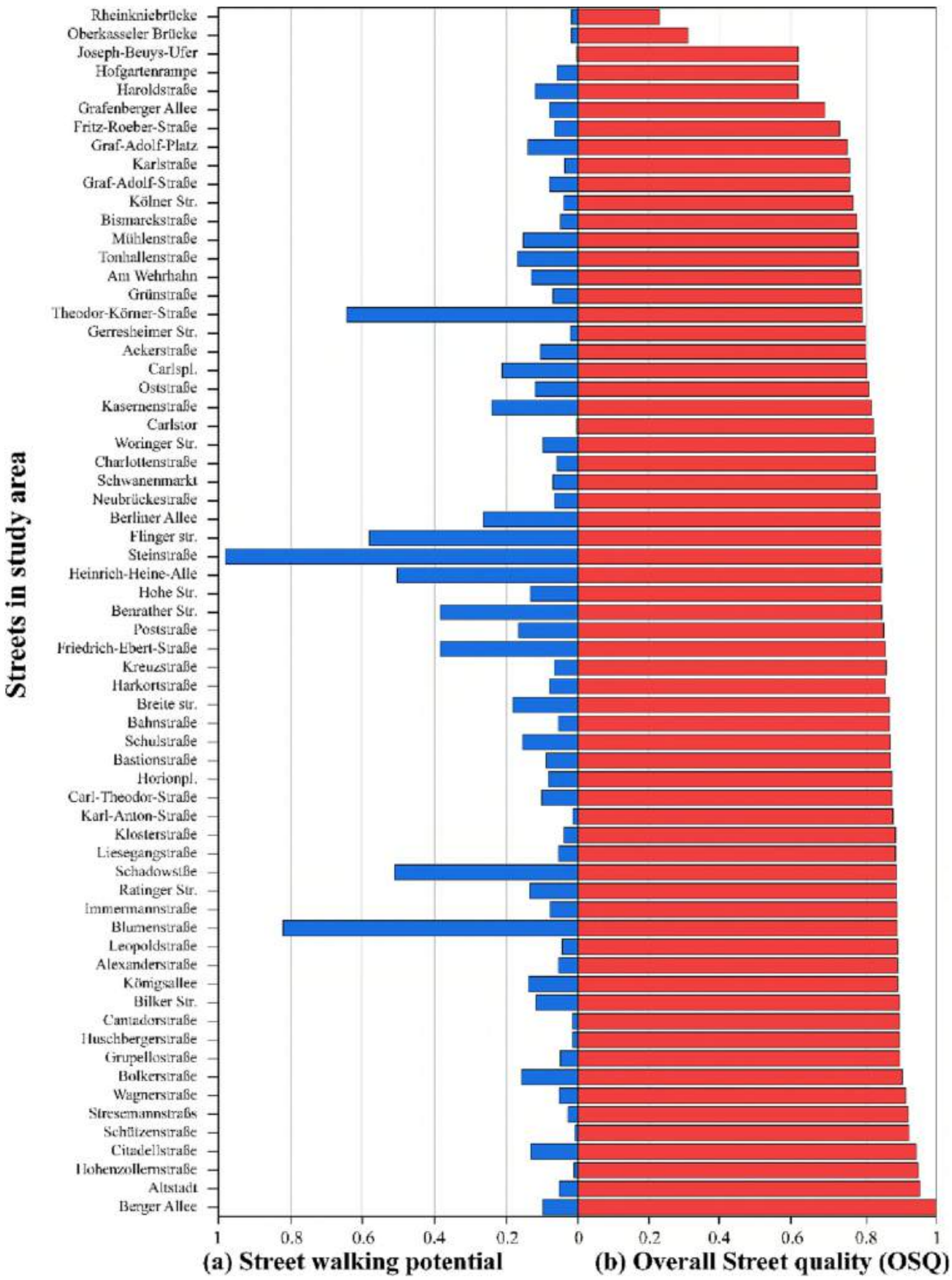


Fig. 11. Ranking of street walking potential and OSQ.

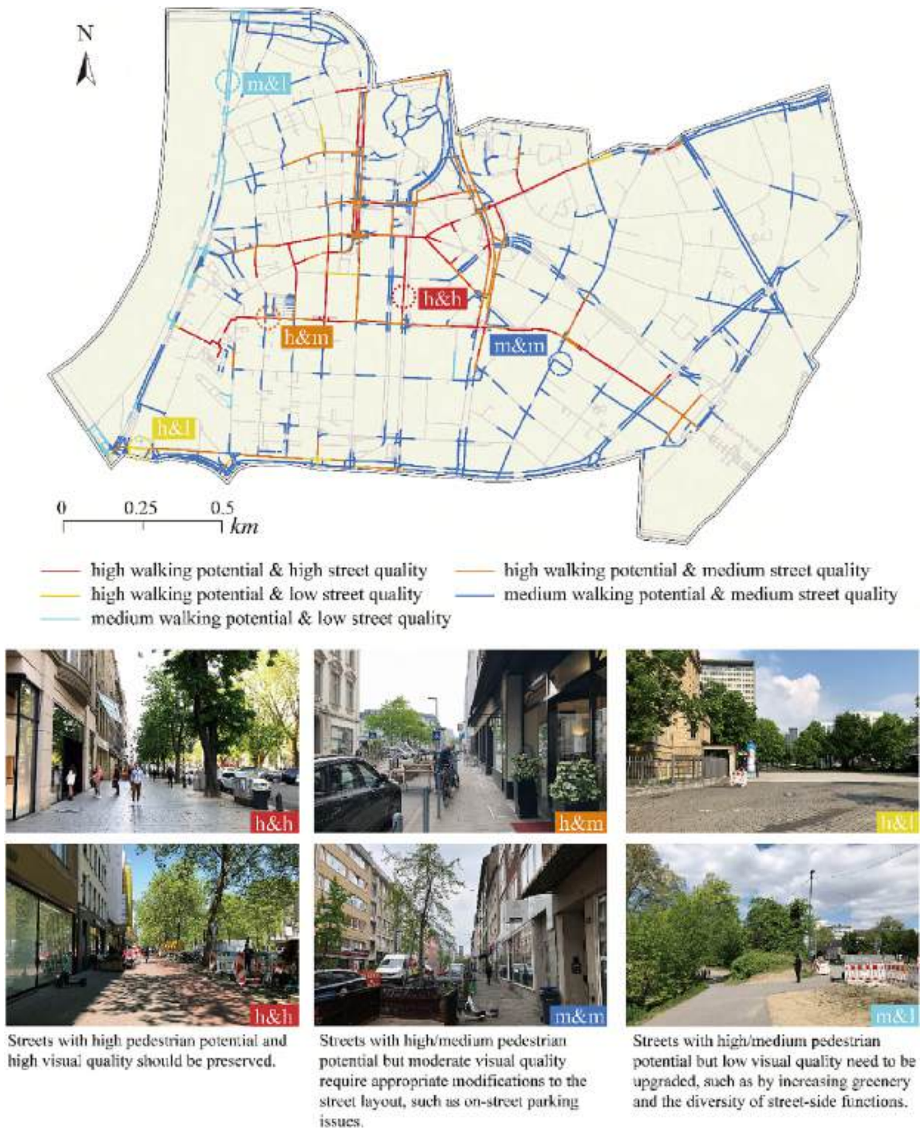


Fig. 12. Identifying priority for regeneration of street segments in high and medium walking potential areas.

4.7. *Identifying the priority of urban street renewal at the zoning level*

We compared the OSQ in accordance with the functional zoning criteria of Düsseldorf (https://www.duesseldorf.de/geoportal.html). The OSQ in Fig. 9 have not undergone normalization and can be more clearly seen to correlate with other metrics. At first glance, the residential area receives the highest OSQ of0.540, followed by the core area and common area with 0.712 and 0.708 respectively. Notably, the core area and residential area have a pedestrian-friendly street environment despite the lack of greenery, i.e., the greenness are poor (0.135 and 0.118), however, the remaining three indices are relatively high, especially walkability reaches 0.793 and 0.698 respectively. Likewise, the mixed-use area and the common area receive similar individual scores, i.e., high greenness and enclosure, medium walkability. Given that there are no buildings in the green space, it makes sense that the imageability score, which is most influenced by buildings, is relatively low. Based on the analysis, we suggest more greenery needs to be planned on both sides of the streets in residential areas. Moreover, there is a need to increase the width of pedestrian paths in mixed-use and common areas or to improve accessibility for both pedestrians and vehicles by converting streets into shared spaces. Increased walkability can boost the economic value and street vibrancy in these urban areas with mixed-use properties.

Since the core area, mixed-use area, and common area have comparable functional features. We combined them as mixed-functional areas and analyzed the geographical distribution of street-level commercial density in relation to street quality using the latest POI (downloaded in June 2022). Despite displaying a low pedestrian potential in Fig. 8, we noticed that areas B and D had a positive correlation between commercial density and OSQ and also exhibited a patchy and striped pattern according to the network structure (Fig. 10). The same phenomenon is evident in area E, which indicates a medium commercial density and a medium-high OSQ. Combined with the results in Fig. 8, we concluded that commercial density constitutes a sufficient condition for street quality.

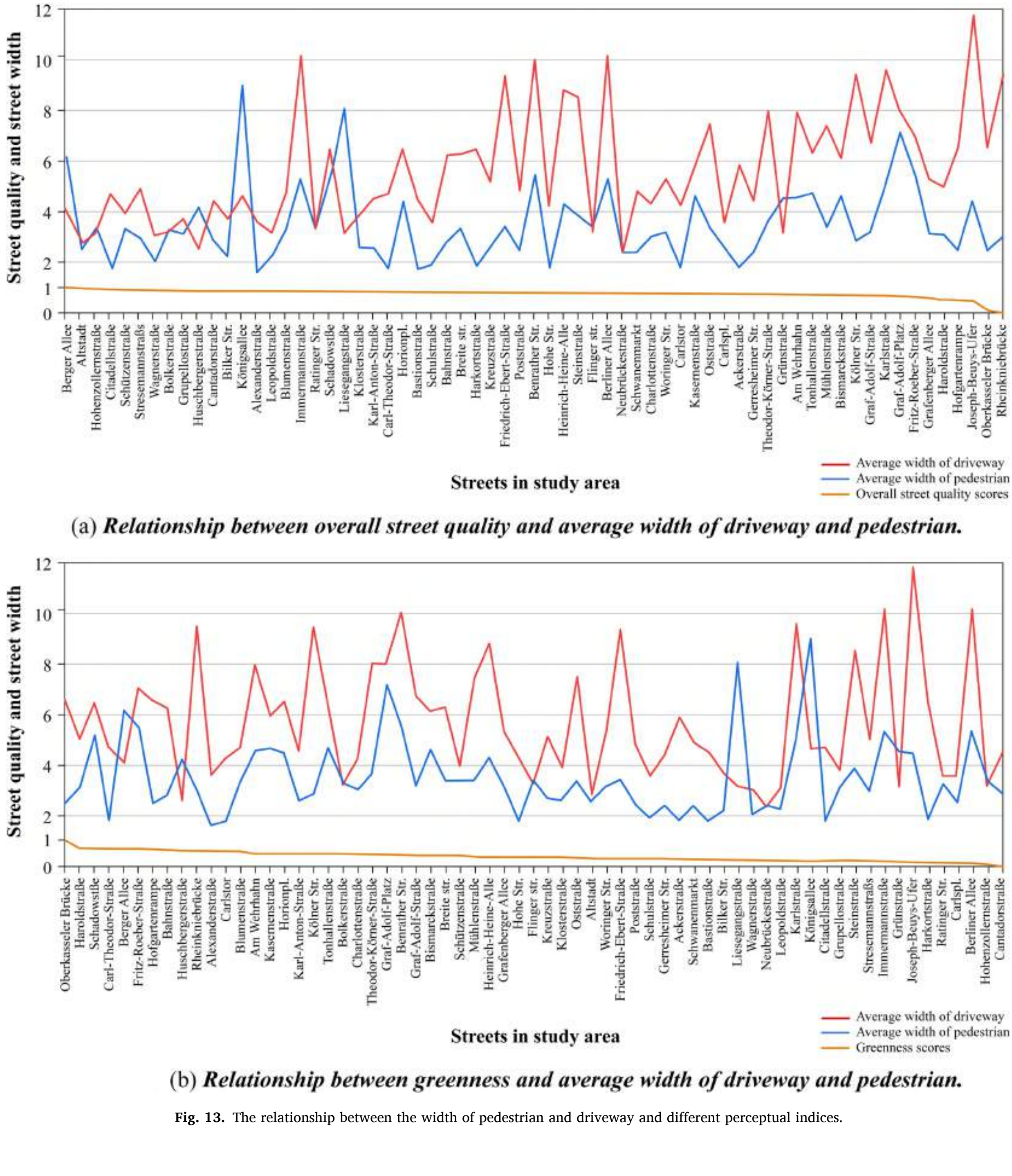
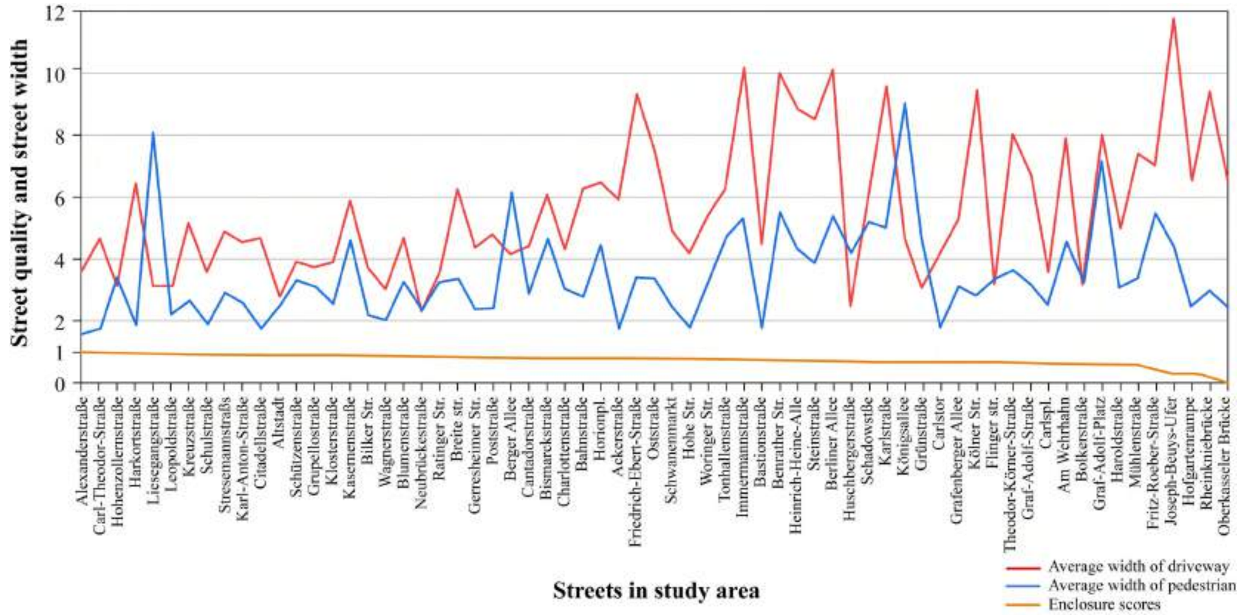


Fig. 13. The relationship between the width of pedestrian and driveway and different perceptual indices.

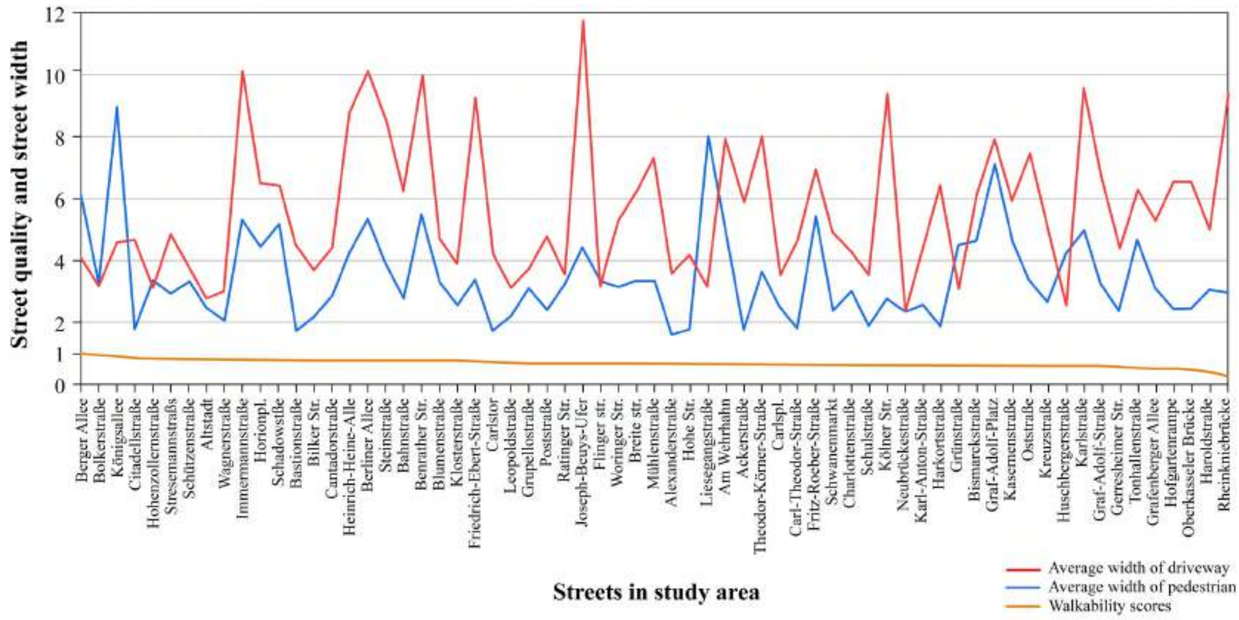
4.8. Identifying the priority of urban street renewal at the street level

Fig. 11 ranks the OSQ from lowest to highest and the related walking potential to visualize the priority of street renewal. The data have been normalized. In general, all streets exhibit positive street quality except for bridges, ranging from 0.6 to 1. Regarding quality ranking, the renovation of low-quality streets needs to be given priority, e.g., Joseph-Beuys-Ufer, Hofgartenrampe, Haroldstraße, and Grafenberger Allee. It is also worth noting that some urban streets with significant pedestrian potential can be renovated on their existing bases to enhance spatial quality, e.g., Steinstraße, Theodor-Körner-Straße, and Blumenstraße.

Urban renewal can be identified at the street level by a combined analysis of pedestrian potential and street quality. Since street segments have varied ratings, further identification of road segments is required. Fig. 12 depicts the status of different street segments in areas of high and medium pedestrian potential. Yellow, light blue, blue, and orange are



(c) ***Relationship between enclosure and average width of driveway and pedestrian.***

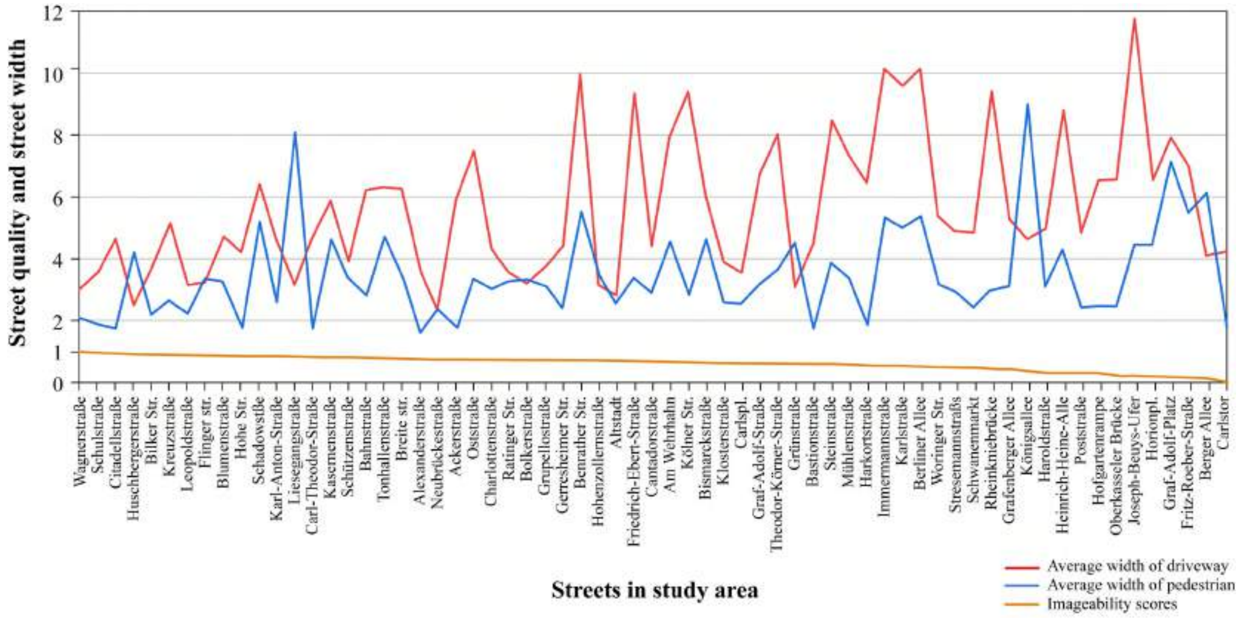


(d) ***Relationship between walkability and average width of driveway and pedestrian.***

Fig. 13. (*continued*).

suggested as the order of priority for the renewal. The effect of the transformation can be referred to as the high-quality street areas (red). Based on selected streetscape photographs, we found that the high-quality streets have better enclosed and high-occupancy pedestrian paths, tall trees and shade formation, personalized street facades, and a moderate amount of people. In contrast, the medium-quality streets (orange and blue) have less pedestrian width and closer street parking to the sidewalk, yet still have attractive facades and a moderate amount of outdoor furniture. However, low-quality streets (yellow and light blue) are more open and lack suitable street furniture and commercial services.

Based on the above analysis, we hypothesize that the widths of the sidewalk and driveway are associated with perceptual indices. Considering the structure of street rail traffic in Germany, we measured single-sided streets for our study. Fig. 13 indicates that the width of the driveway increases progressively as the quality of the street declines, but the width of the sidewalk remains relatively constant. The driveway and sidewalk widths tend to be equal on high-quality streets. We did not



(e) ***Relationship between imageability and average width of driveway and pedestrian.***

Fig. 13. (*continued*).

detect a clear correlation between greenness and street width due to the independent effect of it (Fig. 13b). There is a significant negative correlation between enclosure and pedestrian and driveway widths. The higher the enclosure, the closer the pedestrian and driveway widths are, and vice versa (Fig. 13c). A negative correlation with width also found in imageability (Fig. 13e). We found that reducing the width of the driveway is conducive to walkability since the driveway with high walkability is less than 5 m (Fig. 13d). In summary, the overall quality of streets, enclosure, and imageability are negatively correlated with the widths of sidewalks and driveways. The widths of sidewalks and driveways in high score areas are all clustered in the range of 2–6 m, which provides a reference for constructing human-scale streets in urban areas.

5. Discussion

5.1. Objectively measuring the street quality from pedestrian view as human-scale planning practices

We conducted an urban-scale but fine-grained measure of street quality using a combination of macroscopic urban data and fine-grained self-collected datasets. Besides, we analyzed the differences in visual perceptions from driveway and sidewalk perspectives to correct the current measurement approach, allowing for a more precise determination of the margin of error and authenticity of the current study. This enhancement can contribute to understanding human-centered urban planning and street design. In addition to aiding in modifying earlier subjective and experience-based measurements, it can be used as supplemental material for urban design theory.

In terms of scores for greenness, enclosure, and imageability, the results of the GSV and SPPV studies were comparable. Compared to GSV, SPPV indicates that pedestrians are exposed to less street greenery on the main streets in urban centers and more in green spaces and suburban areas. In addition, secondary streets have a lower degree of enclosure. Regarding walkability, the results of the pedestrian view are higher than the driveway view, indicating that prior studies employing GSV data may have underestimated street walkability. Walkability and imageability are essential for studying urban vitality, but the visual elements that define them are limited due to technology. It may lead to inconsistencies between the results and the participants' experiences. For instance, the western riverfront of the study area is a highly frequented pedestrian thoroughfare, but it receives low scores.

5.2. The significance of perceptual throughput and walking potential to build walkable cities

We integrate the pedestrian potential and street perceptual quality to identify and prioritize areas for renewal at the zoning-, street-, and street segment levels. The measurement approach can be applied to cities to aid decision-makers with spatial identification and strategy development. From a planning perspective, the high and relatively high scores of sampling points account for 28.60 % and 31.32 %, and the spatial layout of these areas can be studied and used elsewhere. However, there are still areas with medium (23.35 %), relatively low (13.21 %), and absolutely low (3.32 %) scores that need to be strategically targeted for street renewal and prioritized in future planning.

Each perceptual metric affects the visual quality of streets and path choices in specific ways. Here we present recommendations for building walkable cities from five indicators: (1) The width of sidewalks and driveways with high greenness scores is 3 m and 4 m, respectively, and these narrow streets are often suitable for building harmonious natural landscape. When the width of the driveway reaches 6 m (i.e., main streets), the greenness is relatively high again. Therefore, special attention needs to be paid to enhancing the greenery coverage of the streets that are visited daily as well as the main roads. (2) It should be emphasized that people prefer to travel around in the narrow, enclosed commercial streets and residential areas. However, they also prefer to entertain in open spaces, as evidenced by participant experience. This indicates that our approach is more appropriate for urban areas than for suburbs. (3) The equation for enclosure has shown good performance after our reformulation. We found that well-connected streets attract pedestrians and result in higher imageability. Therefore, we propose

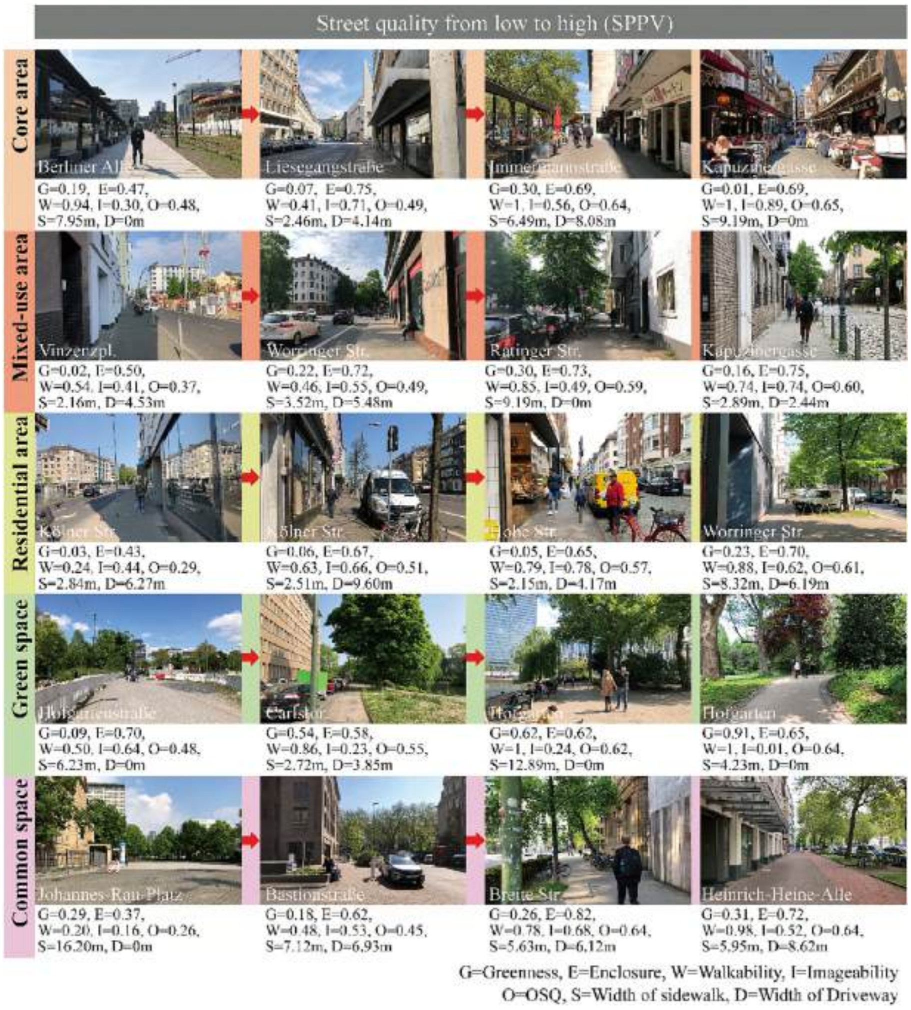


Fig. 14. Samples of transformation potential in different urban functional areas.

that enclosure can be improved, particularly in residential and commercial areas, by increasing vertical elements (more trees, street signs, etc.) or decreasing horizontal elements (i.e., reducing the width of the driveway). (4) Both GSV and SPPV demonstrate that walkability is positively proportional to the enclosure. Likewise, the width of the driveway and the sidewalk affects the walkability. We found that the walkability is enhanced when both are roughly 4 m and tend to be equal. This finding is helpful for street planning in the new urban area. (5) Landmarks and buildings with distinctive features play an essential role in imageability. There is a negative correlation between the exposure of the building and the width of the street. At the micro level, it is suggested to increase façade decoration, advertising signs, and street amenities to improve pedestrians' memory of the surroundings; at the macro level, 2-5 m driveways and sidewalks on each side may raise the exposure of the buildings and the sense of enclosure. Other approaches to imageability include buildings with identifiers, courtyards, plazas and parks, outdoor recreation facilities, and major landscape features.

5.3. Application of pedestrian-oriented streetscape transformation strategies

Comparing the spatial quality of streets in various urban functional areas enables the establishment of a comprehensive spectrum of fine-grained street construction (Fig. 14). The graphic indicates that the degree of enclosure and walkability improves the quality of the core area. Additional street amenities, street-side shops, outdoor dining space, and shade also enhance street quality. The combined effect that people attract people occurs in this area (Gehl, 1987). The mixed-use area exhibits the critical role of greenness, enclosure, and walkability. Sidewalks and driveways often coexist here; therefore, the appropriate width ratio and buffer zones in-between will affect pedestrian safety and quality. Buffer zones include greenbelts, bike lanes, railings, on-street parking spots, etc. The overall street quality in a residential area can be improved by opening the street façade, enhancing the vitality of sidewalk, and planting street greenery. Adequate green shade can provide shade to and parking spaces while stores along the street should be open to the public to provide convenience and social opportunities. The overall street quality in the green space can be enhanced by creating relatively narrow paths within and around the park to raise the exposure to greenery. The common area has the highest street width of all functional zones since it mainly serves urban mobility and commuting. In this case, green belts can be considered a barrier between pedestrians and automobiles, along with bicycle lanes and street parking spots. External eaves on the ground floor or semi-indoor space can further boost pedestrian mobility on rainy days. To conclude, street furniture, street greening, and open building facades are effective methods for enhancing urban street quality. It is important to note that planners must draw up retrofitting plans based on the requirements of various functional zones and commuting standards.

5.4. Limitations and further work

Despite the contributions mentioned above, there are still limitations in our study. Firstly, our revised formula applies to measuring urban streets and has a mediocre performance in measuring open spaces, resulting in deviations in scores and participant experience. Secondly, 2292 of the streetscape images we downloaded were captured during the spring and summer months, specifically between April and October, accounting for 86.49 % of the total sample size. This finding indicates that there is no significant bias in the elements, including greenery, thus proving the reliability of the study results. Nonetheless, it is important to note that the inherent limitation of street view data acquired through web crawling is the time of image capture, which exists in all studies using this method. To mitigate this limitation, future studies using this type of data could have greater control over the timing of street view image acquisition as data availability increases. Third, a time discrepancy between the pedestrian view image and the normal Google Street View (GSV) image may impact the results of the analysis. Future comparison work needs to minimize the time differences of each street view image. Fourth, our calculation of the total street score is obtained by assigning the same weights to the four indicators; in fact, different indicators may reflect different importance in terms of total street quality. Furthermore, Furthermore, while our decision to select streetscape images focusing on front and rear views aligns with environmental psychology principles and carries forward the methodology and findings from previous studies (Kim et al., 2021; Ye, Zeng, et al., 2019), it might not entirely capture the comprehensive built environment. Current research trends to employ four views, 360° perspectives, or panoramic imagery, all of which provide a more holistic representation of the built environment. Consequently, it is advisable for future research to embrace a multi-view approach. Nevertheless, the challenges and the substantial workload associated with manual acquisition must not be underestimated.

6. Conclusions

As a prospective study combining the measurement of street walking potential and perceptual quality, this study improves the current measurement approach by replacing the vehicular perspective with the pedestrian perspective while providing a solid reference for municipal units to develop spatial identification and operational standards. In addition, this study reveals the dual relationship between the deep-learning-driven research paradigm of visual features of street environments and the assessment of pedestrian potential. The combined analysis of walking potential and streetscape quality to identify renewal space and priorities can provide a theoretical basis for further planning.

We conclude that: (1) perspective differences have the most significant effect on walkability. It also affects other indices in different geographic locations; (2) street quality in various functional areas differs slightly in individual perceptions and thus requires retrofitting methods for specific zones; (3) since different segments of a street exhibit varied spatial qualities, urban renewal should be implemented to each segment rather than the whole street; (4) street commercial density is sufficient condition for street quality; (5) overall street quality, enclosure, and imageability have a negative correlation with street width. When the widths of pedestrians and driveway on one side are in the range of 2 to 6 m and tend to be equal, they are more pedestrian-friendly.

CRediT authorship contribution statement

Jin Rui: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The author declares no conflict of interest.

Data availability

Data will be made available on request.

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Supplementary data

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Exploring the association between the settlement environment and residents' positive sentiments in urban villages and formal settlements in Shenzhen

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ABSTRACT

The promotion of residents' positive sentiments is essential for achieving the Sustainable Development Goals. However, there is limited evidence on the effect of the settlement environment (SE) on sentiment, especially in urban villages (UVs). By combining affective geography and social media data, this study aims to analyze the residents' sentiments in UVs and formal settlements (FSs) in Shenzhen, while exploring the underlying mechanisms of SE variables that influence the positive sentiment index (PSI). The Weibo text data was analyzed using Natural Language Processing to obtain the PSI. Furthermore, we employed an XGBoost model, Shapley Additive Explanations and Partial Dependence Plots to explore relationships between SE variables and the PSI. We utilized the Interpretative Structural Modeling and Bayesian Network to analyze and verify the interdependencies and probabilistic results. The results revealed that the PSI exhibited spatial heterogeneity, with a trend of medium-high-low from central to suburban areas, and a clustering effect of high and low values. For FSs, we recommend enhancing health and well-being by increasing metro facilities, commercial density and fostering walkable neighborhoods. For UVs, prioritizing micro walk accessibility can improve settlement circulation. Additionally, we identified the potential of marginalized UVs to integrate with e-trade and transform into "special economic zones."

1. Introduction

Sentiments are subjective experiences generated by humans in specific situations and are usually accompanied by physical and psychological changes (Ekman, 1992). Positive sentiments reflect a sense of happiness or momentary subjective well-being and contribute to people's overall happiness (Cohn et al., 2009). However, according to the World Health Organization, mental disorders affect 3.8% of the global population, with 280 million people suffering from depression, including 54 million in China (Institute of Health Metrics and Evaluation, 2021). Approximately 16.6% of Chinese adults have experienced mental illness in their lives (Huang et al., 2019). In the 1990s, Anderson and Smith (2001) introduced the concept of affective geography, which explored the relationship between people, sentiments, and space, revealing the temporal, spatial, and social characteristics of sentiment. In urban studies, examining the sentimental experiences of residents in relation to their surroundings can enhance spatial quality and address socio-spatial disparities in cities. Such endeavors are integral to achieving the United Nations' Sustainable Development Goals (SDGs) of promoting "good health and well-being (SDG3)" and creating "sustainable cities and communities (SDG11)" (Chiesura, 2004; Kong et al., 2022a; Plunz et al., 2019; UN, 2015).

Rapid global urbanization and urban population explosion have led to negative impacts on human well-being and sustainable environmental development. It has resulted in well-being issues such as social inequality (Wu and Rao, 2017; Zhu et al., 2019) and housing imbalance (Kong et al., 2022b), as well as environmental issues including air pollution (Liu et al., 2022), land resource depletion (Maja and Ayano, 2021), and a significant increase in carbon emissions (Wang et al., 2022). According to China's 2020 Census, 63.89% of its population resides in cities (Statistics, 2021). Reasons affecting residents' sentiments include family status, economics, marriage, and genetics, but environmental indicators, accounting for 40–50% of subjective sentimental impression variables (Melton, 2018). The high-density built environment and infrastructure of large cities can lead to negative sentiments (Morris and Guerra, 2015; Zhu and Fan, 2018). The residential

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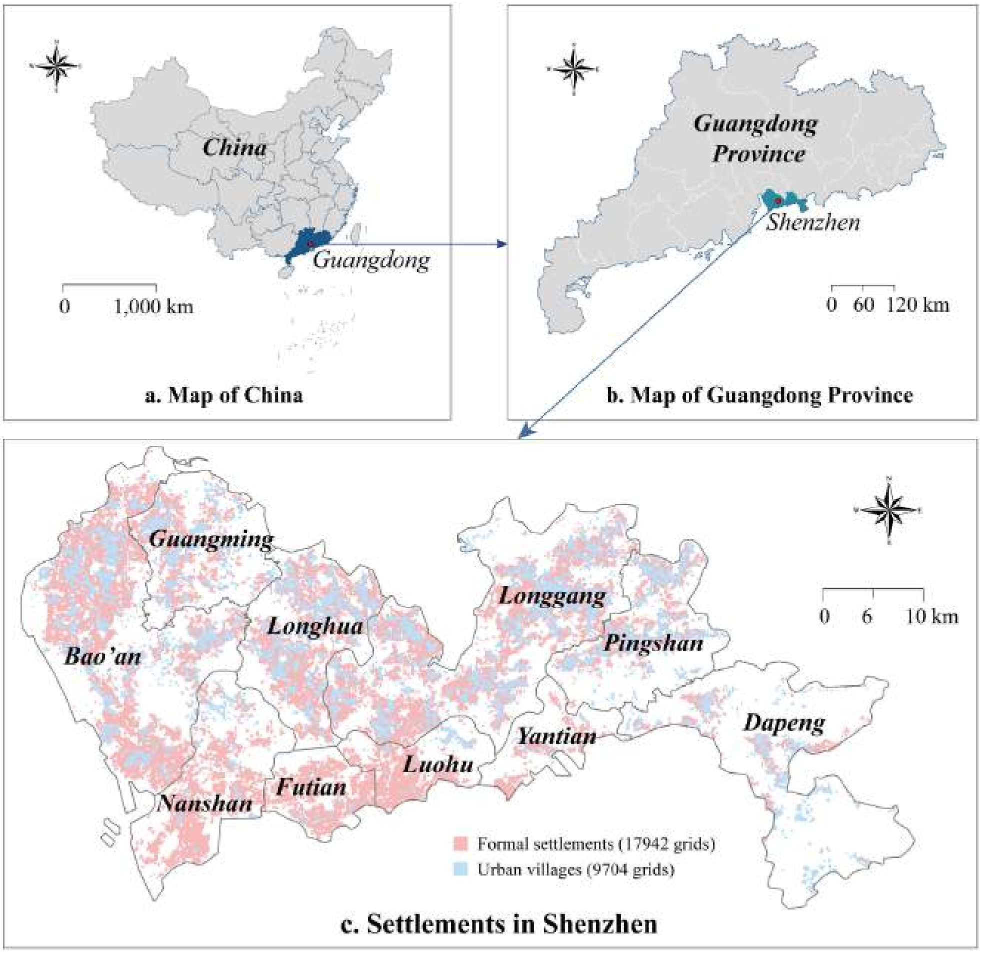

Fig. 1. Study area. (a) Map of China, (b) map of Guangdong Province, and (c) settlements in Shenzhen.

environment, in particular, plays a crucial role in the sentimental state of residents. On the one hand, urban populations spend an average of 87% of their time indoors and about half in their neighborhoods (Klepeis et al., 2001). On the other hand, urban residential land use accounts for 20–32% of the total urban area (Chinese Ministry of Construction, 2011). Therefore, understanding the complex relationship between the SEs and residents' sentiments in Chinese big cities is critical.

Shenzhen, a representative of China's metropolis, has experienced a 54-fold increase in population in 40 years (Statistics, 2021). However, the city's rapid urbanization has given rise to Urban Villages (UVs). These UVs have been criticized by academics for their high-density built environment, disorganized planning layout, and unappealing appearance. In line with China's latest "*New Urbanization Implementation Plan during the 14th Five-Year Plan period (2021–2025)*" (National Development and Reform Commission, 2022), the Shenzhen Planning & Natural Resources Bureau (2019) released the "*Shenzhen Urban Village Comprehensive Improvement Plan (2019–2025)*" to address the environmental problems of UVs, advocating a change from demolition to renovation-led UV regeneration policy. Thus, research on urban settlements that encompasses the mechanisms of the SE to drive positive sentiments among residents will offer valuable planning insights and facilitate the creation of healthy communities and the regeneration of UVs.

Previous studies relied on conventional methods of data collection, including questionnaires (Wang et al., 2021b) and observation techniques (Evenson et al., 2016; Wang et al., 2021b). Conventional methods possess certain limitations, as they often involve small sample sizes and yield passive, static information. Furthermore, the process of acquiring data is time-consuming (Duan et al., 2022; Gao et al., 2019; Liu et al., 2021; Zhang et al., 2023). The rise of social media in the Internet era has revolutionized the way people express their sentiments and share information, with platforms such as Twitter, Facebook, Weibo, and TikTok. Weibo, one of the largest social media platforms in China, holds a wealth of user sentiment data (Liu et al., 2021; Wang et al., 2020; Wang et al., 2015). Unlike traditional data sources, Weibo data is unstructured, real-time, and includes spatial location information posted by users. Weibo text captures users' sentiments and perceptions. These "human-based" datasets have large sample sizes and high geographic precision, making them ideal for sentiment analysis.

Researchers have increasingly used social media data and sentiment analysis to investigate the relationship between residential sentiment and a range of natural, social, environmental, and economic variables (Chen et al., 2016; Guo et al., 2022; Kong et al., 2022a; Wang et al., 2020; Zheng et al., 2019). Social media data is also being utilized to explore urban built environments. Duan et al. (2022) analyzed the elements of the built environment from a youth perspective through sentimental hashtags and intensity to enhance the well-being of urban youth, and Chen et al. (2020) used Twitter data to study the link between the spatial distribution of geo-tagged tweets and key features of the built environment. While these studies have exemplified the

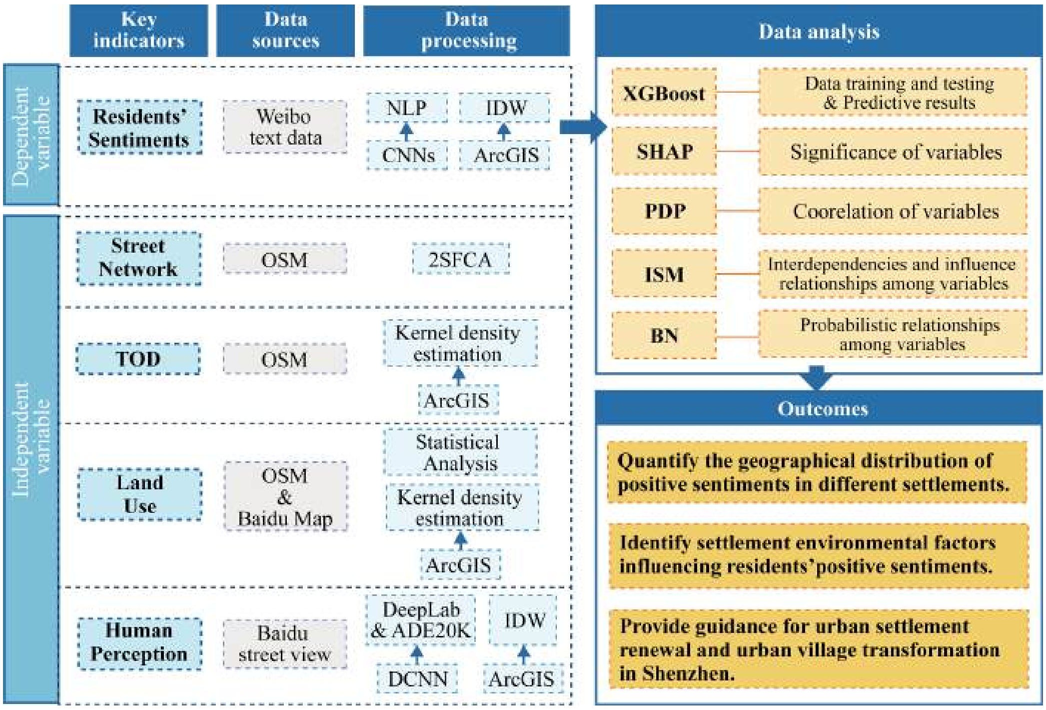

Fig. 2. Theoretical framework.

effectiveness of social media big data for quantifying sentiment and exploring urban spaces, none have yet focused specifically on urban settlements, nor have they considered the differences between FSs and UVs. In addition, due to technical and algorithmic limitations, the current use of methods such as Word2vec (Zhang et al., 2023) lacks comprehensive consideration of the semantic content, leading to bias in the veracity of the data results (Liu et al., 2021). Fortunately, with the substantial advancements in natural language processing technologies (NLP) in recent years, existing techniques have been able to support efficient analysis of large-scale text data. It is imperative to merge advanced NLP with urban studies to facilitate comprehensive and in-depth mining and achieve high precision measurement of SE.

This study aims to address two significant research gaps. Firstly, there is a lack of focus on residents' sentiments in settlements, particularly with regards to differentiating between various types of settlements. Secondly, few studies discussed the relationship between residents' sentiments and the SE, as well as the validation at the methodological level. To bridge these gaps, the first research question was formulated: How do different SE variables influence residents' positive sentiments? Based on this, a further question was proposed: What measures should be undertaken to enhance the SE to foster residents' positive sentiments? The novelty of this research lies in its specific focus and the integration of interdisciplinary approaches. Firstly, we combined sentiment geography and social media data to examine the sentiments of residents in UVs and FSs. Secondly, we employed multiple machine learning models to explore the underlying mechanisms and complex relationships between the SE and PSI. By validating the probabilistic results, this study contributes to a deeper understanding of how the SE influences residents' sentiments. Thirdly, the study offers valuable insights for the urban transformation in Shenzhen through differentiated settlement planning approaches.

We collected Weibo text data to quantitatively measure the sentiment of Shenzhen residents using a deep learning-based NLP model. We used XGBoost, SHapley Additive exPlanations (SHAP), Partial Dependence Plot (PDP), Interpretive Structural Modeling (ISM), and Bayesian Networks (BN) to comprehensively assess and validate the numerical and logical relationships between the SE variables influencing the PSI. Our study consists of the following steps: (1) mapping the PSI of residents in FSs and UVs by NLP techniques; (2) training and testing datasets using XGBoost; (3) analyzing the importance of SE variables to the PSI using SHAP; (4) analyzing the synergistic effects of multiple SE variables and the nonlinear relationship with the PSI using PDP; and (5) inferring the logistic framework of variables using ISM and validating the framework by BN.

The remaining sections are structured as follows. Section 2 describes the conceptual framework for this study, the data collecting and processing procedure, and the modeling principles of different models. Section 3 presents the results of the study, including the contribution of SE variables and associations with the PSI. Section 4 provides planning recommendations, research contributions and limitations. Section 5 concludes the article.

2. Data and methodology

2.1. Study area

Considering the unique urbanization trajectory of Shenzhen, our focus is on FSs and UVs in Shenzhen. We created a hexagonal study unit with a side length of 100 m in ArcGIS. We defined the study unit as an UV when the area of UV buildings is larger than that of a FS. The AOI data of UVs and the building data from OSM was obtained in January 2023. The spatial distribution of UVs is presented in Fig. 1, where they are represented by the color blue, comprising a total of 9704 units (35.1%). Conversely, FSs are depicted in pink, encompassing a total of 17,942 units (64.9%). Shenzhen, an early special economic zone established during China's reform and opening up in 1978, has evolved into a preeminent exemplar of modern Chinese metropolises. The city can be broadly categorized into the central area comprising Nanshan, Futian, and Luohu (District), the suburban regions encompassing Bao'an, Longhua, Yantian, and Longgang, and the outlying suburbs

Table 1
Description of the variables and calculation of the formula.

Domains	Variables	Definition and formula
Dependent variable		
Sentiment	PSI	Average positive sentiment index in each grid (index)
Independent variables		
Street network	Street density	Street length/grid area (km/km^2)
	Walk accessibility Automobile accessibility	For the accessibility of walking and driving/automobile, we selected the Gaussian 2SFCA method for calculation. First, for each $Settlement_j$, we define the area of settlement as the service catchment S_j. Second, search all population location points within a search radius d_0 and count the total service population P_k. Third, for P_k of each $Settlement_j$, weighted by the distance decay function $G(d_{kj}, d_0)$. Finally, calculate the ratio between $S_j$and P_k as the walk supply-demand ratio for each settlement. The formula is shown as follows Eq. (1): $$R_j = \frac{S_j}{\sum_{k\in\left\{d_{kj}\leq C_j\right\}} G\left(d_{kj},\, d_0\right) P_k} \quad (1)$$ Where R_j is the supply-demand ratio of settlement location j. S_j is the area of settlement. P_k is the total service population in the search radius d_0. According to (Wang et al., 2013), we select 1,2 km and 7,6 km as the reasonable walking and driving distance d_0. (d_{kj}, d_0) is the Gaussian function, and d_{kj} is the walking distance between location j and population location k. The formula of the Gaussian function is shown below Eq. (2): $$G\left(d_{kj}, d_0\right) = \left\{ \frac{e^{-\frac{1}{2}\times\left(\frac{d_{kj}}{d_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, d_{kj} \leq d_0 \; 0, d_{kj} > d_0 \right. \quad (2)$$ For each location i, given a spatial distance d_0, and the supply-demand ratio R_l of the supply location l falling within the scope is weighted using a Gaussian equation. The weighted ratios are then summed to obtain the spatial accessibility A_i^F of demand location i Eq. (3). $$A_i^F = \sum G\left(d_{kj}, d_0\right) R_l \quad (3)$$
TOD	Bus route density	Bus line meters/grid area (km/km^2)
	Bus station density	Kernel density of bus stations/grid (index)
	Metro route density	Metro line meters/grid area (km/km^2)
	Metro station density	Kernel density of bus stations/grid (index)
Land use intensity	Building Coverage Ratio (BCR)	The ratio of the total standing area of all buildings to the total area of the grid Eq. (4). $$BCR = \mathrm{B}/\mathrm{A} \quad (4)$$ Where B and A denote the gross building footprint (km^2) and gross area (km^2).
	Floor Area Ratio (FAR)	The ratio of the gross floor area of all buildings to the total area of the grid Eq. (5). $$FAR = \frac{\mathrm{F}}{\mathrm{A}} \quad (5)$$ Where F and A denote the grass floor area (km^2) and gross area (km^2).
	Land use mix (LUM)	The degree to which those different types of land uses are physically and functionally integrated Eq. (6). $$LUM = -\sum (P_i)(\log P_i) \quad (6)$$ Where Pi the ratio of the ith land type to the total area.
Land use type	Residential density	Number of residential POIs/grid area (counts/km^2), including accommodation services such as communities, apartment, dormitories.
	Commercial density	Number of commercial POIs/grid area (counts/km^2).
	Industrial density	Number of industrial POIs/grid area (counts/km^2).
	Public service density	Number of public service POIs/grid area (counts/km^2).
	Green space density	Number of green space POIs/grid area (counts/km^2).
	Transportation service density	Number of transportation facilities POIs/grid area (counts/km^2).
	NDVI	Standardized Difference Vegetation Index/grid area

(*continued on next page*)

Table 1 (*continued*)

Domains	Variables	Definition and formula	
Streetscape perception	Greenness	Urban green spaces, such as forests, green belts and lawns, have positive implications for the design of urban landscapes Eq. (7). $$G_i = \frac{1}{n}\sum_{i=1}^{n} T_n \quad (7)$$	T_n denotes the tree pixels; S_n denotes the sky pixels; B_n denotes the building pixels; R_n denotes the road pixels; $P1_n$ denotes the pavement pixels; F_n denotes the fence pixels; $S1_n$ denotes the sign symbol pixels; $P2_n$ denotes the person pixels.
	Enclosure	Enclosure refers to how the built environment envelops pedestrians and is closely linked to people's perception of the livability of a place Eq. (8). $$E_i = \frac{\frac{1}{n}\sum_{i=1}^{n} B_n + \frac{1}{n}\sum_{i=1}^{n} T_n}{\frac{1}{n}\sum_{i=1}^{n} R_n + \frac{1}{n}\sum_{i=1}^{n} P1_n + \frac{1}{n}\sum_{i=1}^{n} F_n} \quad (8)$$	
	Walkability	Walkability reflects the overall level of support provided by the outdoor environment for walking Eq. (9). $$W_i = \frac{\frac{1}{n}\sum_{i=1}^{n} P1_n + \frac{1}{n}\sum_{i=1}^{n} F_n}{\frac{1}{n}\sum_{i=1}^{n} R_n} \quad (9)$$	
	Imageability	Imageability is a defining characteristic of a place that endows it with distinctiveness, recognizability, and memorability Eq. (10). $$I_i = \frac{1}{n}\sum_{i=1}^{n} B_n + \frac{1}{n}\sum_{i=1}^{n} S1_n + \frac{1}{n}\sum_{i=1}^{n} P2_n \quad (10)$$	

spanning Guangming, Pingshan, and Dapeng. It does not conform to the classic archetype of an "instant city". Instead, its origins can be traced back to former rural enclaves, now referred to as UVs (Du, 2020). Due to the failure of government-sponsored low-cost housing to meet the population's needs, UVs with lower living costs have taken on the responsibility of providing affordable housing. Currently, an estimated 11 million floating people reside in UVs (SSB-NBSSOS, 2020).

There are 1877 UVs in Shenzhen (Lai and Tang, 2016; Pan and Du, 2021). Between 2005 and 2018, the majority of urban renewal projects in Shenzhen focused on demolishing these UVs, with 482 out of 644 projects geared towards this goal, constituting a notable 48% of the total urban renewal efforts (Pan and Du, 2021). In 2019, the Shenzhen Planning & Natural Resources Bureau (2019) unveiled the "*Shenzhen Urban Village Comprehensive Improvement Plan (2019–2025)*", which aims to comprehensively regenerate these UVs by integrating ancillary facilities, effecting functional changes, and undertaking partial demolition and construction. Covering a vast area of over 99 km^2, this integrated regeneration project encompasses over 54% of UVs in each administrative district.

2.2. Theoretical framework

We have developed a comprehensive framework to measure the positive sentiments of residents and examine their relationships with the SE. The proposed framework comprises five steps, which are illustrated in Fig. 2. First, we selected residents' sentiment as the dependent variable, and street network, Transit-Oriented Development (TOD), land use intensity, land use type, and streetscape perception as independent variables. Second, we chose appropriate data sources for each variable. Third, we used NLP to calculate the PSI based on Weibo text data. We analyzed the street network using Two-step floating catchment area method (2SFCA), processed TOD and land use indexes using point of interest (POI) data, and performed semantic segmentation of Baidu Street images using Deeplab V3+. All the processing results were integrated and visualized in ArcGIS. Fourth, we selected XGBoost to train and test our dataset. Then we conducted a comprehensive analysis using SHAP and PDP to explore the significance of variables and their multivariate correlations. Additionally, we elucidated the interdependencies and influence relationships among variables using ISM model and validated the probabilistic results using BN.

2.3. Selection of variables

Table 1 displayed the dependent and independent variables chosen for this investigation, along with their corresponding explanatory and computational formulas.

2.4. Data collection

This study utilized open data sources, including Weibo text data, POI, street and building footprint data. We retrieved Weibo text data from the Sina Weibo website (https://m.weibo.cn/) in Shenzhen from June to December 2022, containing latitude and longitude of postings, text information, user IDs, and retweet counts. POI data was collected in January 2023 from Baidu Maps (http://map.baidu.com/). It comprises a comprehensive catalog of real-world geographic entities that includes spatial and attribute information, such as names, spatial coordinates, and categories. The building footprint and street data consist of building spatial coordinates, base contours, floors, and streets at different levels, which were obtained from OSM (https://www.openstreetmap.org) in January 2023.

The Street View Image (SVI) data was obtained by accessing the Baidu Street View API (https://api.map.baidu.com/lbsapi/) in January 2023 (Fig. 3). Sampling of the SVI was conducted at 50-meter intervals along the streets using ArcGIS. We used uniform camera settings and image resolution to ensure consistent perspective, including a horizontal

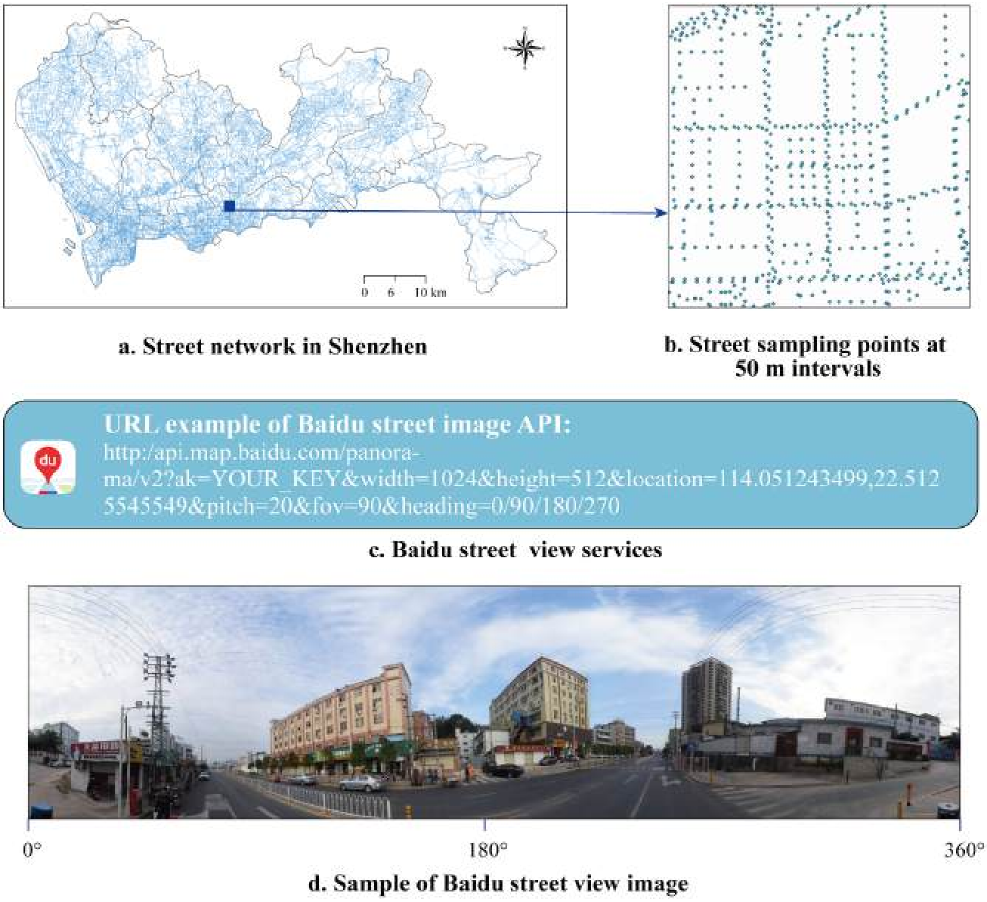

Fig. 3. Downloading Baidu SVIs (a) street network in Shenzhen, (b) street sampling points at 50 m intervals, (c) Baidu street view services, and (d) sample of Baidu SVI.

field of view of 120° and a fixed camera angle ("pitch") of 0° for upward and downward views. At each sampling point, images were captured at 0°, 90°, 180°, and 270° angles, and then stitched together using OpenCV to generate panoramic photos.

2.5. Data processing

2.5.1. Sentiment analysis using NLP

In the field of NLP, we selected Bidirectional Encoder Representations from Transformers (BERT) model for sentiment analysis. Deep

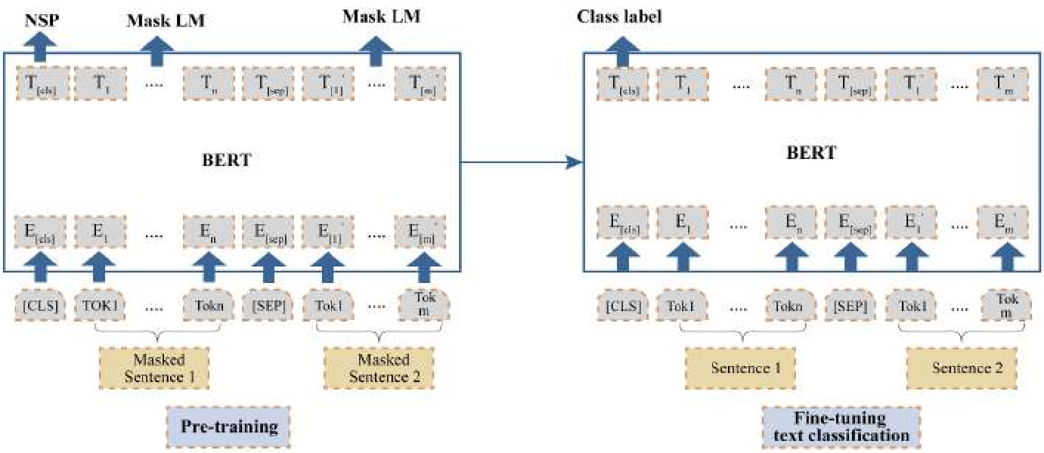

Fig. 4. The structure of BERT.

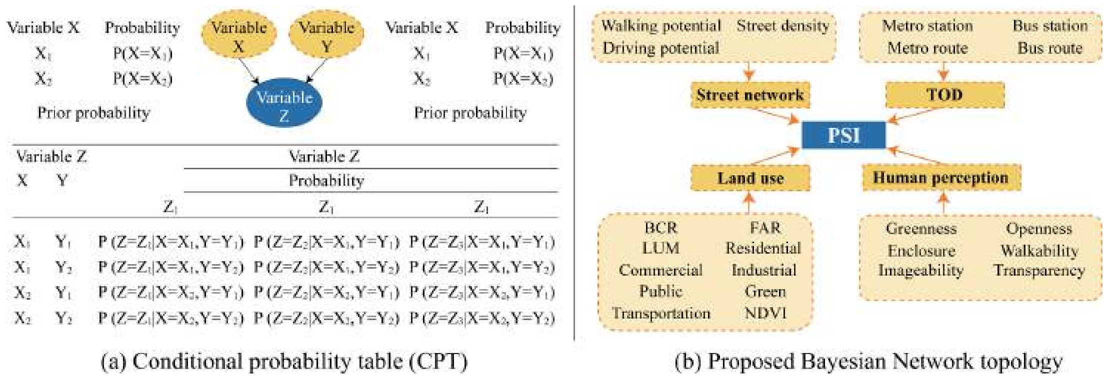

Fig. 5. CPT and proposed BN topology. (a) Conditional probability table. (b) Proposed Bayesian network topology.

learning-based BERT outperforms traditional models because its sentiment results are dynamically influenced by the text surrounding the words. The versatility of the pre-trained BERT model allows it to be fine-tuned for various natural language processing tasks. We use NLP to implement sentiment analysis of text. We grabbed the structure of BERT from the study of Devlin et al. (2018) (Fig. 4). To conduct sentiment analysis, a [CLS] symbol is added to the pre-trained BERT model, which is inserted at the top of the input text. BERT uses Transformer technology (Vaswani et al., 2017), which effectively applies the encoder-decoder model (Sutskever et al., 2014) and attention mechanisms to NLP tasks (Kim et al., 2017). In the supplementary material, we provided a sample of sentiment analysis, attention mechanisms, and model evaluation.

We filtered the Weibo text data by location and obtained 981,678 data for FSs and 519,269 for UVs. Next, we selected four keywords that are highly related to the SE: "UV", "residential", "building", and "neighborhood". We obtained 93,110 items of FSs and 42,540 items of UVs. We used the Chinese pre-training model "weibo_senti_100k" (https://github.com/SophonPlus/ChineseNlpCorpus/blob/master/datasets/weibo_senti_100k/intro.ipynb) for the pre-training dataset.

2.5.2. Semantic segmentation

We employed DeepLab v3+ (Nagata et al., 2020), a state-of-the-art deep learning model designed for semantic image segmentation. Specifically, we utilized the ADE20k pre-training dataset, which is a publicly available dataset for semantic segmentation published by the MIT CSAILVision team (He et al., 2023). This dataset consists of 27,574 annotated scene images from 150 categories, encompassing urban environments. By achieving accurate segmentation results, we were able to establish a foundation for calculating human-perceived SE.

2.5.3. eXtreme Gradient Boosting (XGBoost)

We used XGBoost to train and test the data and obtained the fit and predictive accuracy. This is critical for SHAP and PDP analyses, as they are based on the prediction results of XGBoost.

XGBoost is an efficient extension of the gradient boosting algorithm, designed for building decision trees, that makes optimal use of hardware resources for data-intensive models. It incorporates sparsity-aware data handling and utilizes a weighted quantile sketch for approximate learning, resulting in a scalable package capable of training models with billions of samples. The algorithm constructs a model consisting of n decision trees, with each tree addressing the residuals of the previous tree and leveraging a gradient-based approach to identify new decision trees for building. Notably, XGBoost is not affected by multicollinearity, allowing it to retain all influential features in the model, even if some of them are highly correlated. The algorithm of XGBoost used in this study refer to the research conducted by Chen and Guestrin (2016).

XGBoost was chosen as the model for training and testing in this study due to its performance. The XGBoost model was trained on 80% of randomly selected data, and the remaining 20% was reserved for testing purposes. A 10-fold cross-validation process was employed to ensure model stability. The learning rate of the model was set at 0.001. Utilizing same parameters, we input the research data into decision tree, random forest, support vector machine (SVM), and XGBoost models, respectively. The results demonstrated that XGBoost has the best performance in MSE, RMSE, MAE, and MAPE in both training and testing data sets (Table A 1). Consequently, we chose XGBoost as our model, and the SHAP and PDP analyses were based on the analytical results of XGBoost.

2.5.4. Shapley additive exPlanations (SHAP)

Lundberg and Lee (2017) proposed SHAP, which is inspired by cooperative game theory and provides a way to explain the predictions of complex machine learning models. It is a widely employed method for explaining the predicted results of diverse models. By enhancing the interpretability of machine learning models, SHAP contributes to improving their generalizability and credibility. It builds an additive explanatory model which treats all features as "contributors" (Lundberg and Lee, 2017). For each predicted sample, the model produces a prediction value called the "SHAP value", which is the sum of the values assigned to each feature. The contribution of each feature to the predictions is then interpreted by calculating the corresponding prediction values. SHAP specifies the explanation in Eq. (11):

$$g(z^{'}) = \phi_0 + \sum_{j=1}^{M} \phi_j z_j^{'} \tag{11}$$

where g are one or two features analyzed in the next section, $z^{'} \in \{0,1\}^M$ is the coalition vector, M is the maximum coalition size and $\phi_j \in R$ is the feature attribution for a feature j, the Shapley values.

2.5.5. Partial Dependence Plot (PDP)

The PDP technique can provide insights into the impact of specific factors on the predicted outcome of a machine learning model (Greenwell, 2017). By visualizing the marginal effects of features, PDP enables the examination of the relationship between variables. The partial dependence function is defined as follows:

$$\widehat{f}_{x_S}(x_S) = E_{x_C}[\widehat{f}(x_S, x_C)] = \int \widehat{f}(x_S, x_C) d\mathbb{P}(x_C) \tag{12}$$

Each variable S has its own partial dependence function $\widehat{f}_s$, which can calculate the average value of $\widehat{f}$. x_S is fixed and x_C varies over its marginal distribution $d\mathbb{P}(x_C)$. Both $\widehat{f}$ and $d\mathbb{P}(x_C)$ are uncertain.

Thus, we estimated Eq. (12) by computing Eq. (13) also known as Monte Carlo method:

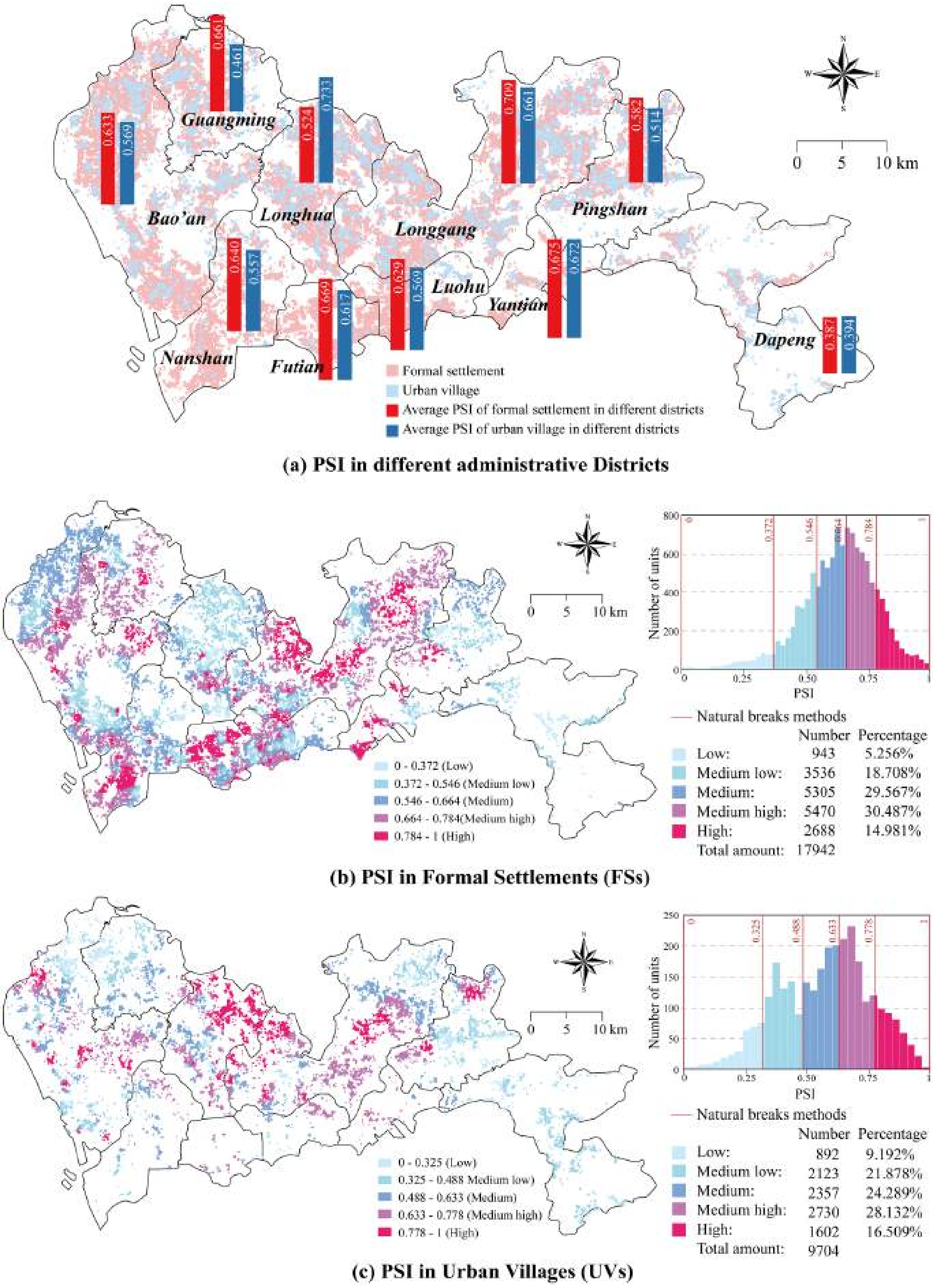

Fig. 6. Distribution and intensity of residents' PSI. (a) PSI in different administrative districts, (b) PSI in FSs, and © PSI in UVs.

$$\widehat{f}_S = \frac{1}{N}\sum_{i=1}^{N}\widehat{f}(x_S, x_{C_i}) \tag{13}$$

where $\{x_{C_1}, \ldots, x_{C_N}\}$ represent the values of training data x_c.

When dealing with multiple classes, PDP employs a One vs Rest (OvR) approach to plot the results. For example, if there are three classes (e.g., class1, class2, class3), PDP will generate three separate graphics. However, one-way PDP only displays average marginal effects, thus losing some local effects. To show hidden local effects and the complex relationships of multiple variables, we extended PDP from one-way to two-way. In the context of two-way PDP calculations, the initial step entails selecting a pair of variables combined with the PSI. Subsequently, the calculation process follows the established steps employed in one-way PDP analysis Eq. (13).

Fig. 7. Results of SHAP analysis by influencing variables. (a.1.) Global feature importance plot in FSs, (a.2.) Local feature importance plot in FSs, (b.1.) Global feature importance in UVs, and (b.2.) Local feature importance plot in UVs.

2.5.6. *Interpretative structural modeling (ISM)*

The ISM model is used in systems thinking and management science to analyze complex systems and their interdependencies. ISM facilitates the identification of cause-and-effect relationships among various components of a system and establishes a hierarchical structure for the system components according to their interdependencies. This hierarchical structure can assist in the identification of critical components within the system and their contribution to the attainment of the system's overall goals.

2.5.7. *Bayesian network (BN)*

The BN is a probabilistic model that uses nodes, arcs, and conditional probabilities to represent variables, dependencies, and quantitative relationships. Fig. 5 illustrated variables X and Y without any parent

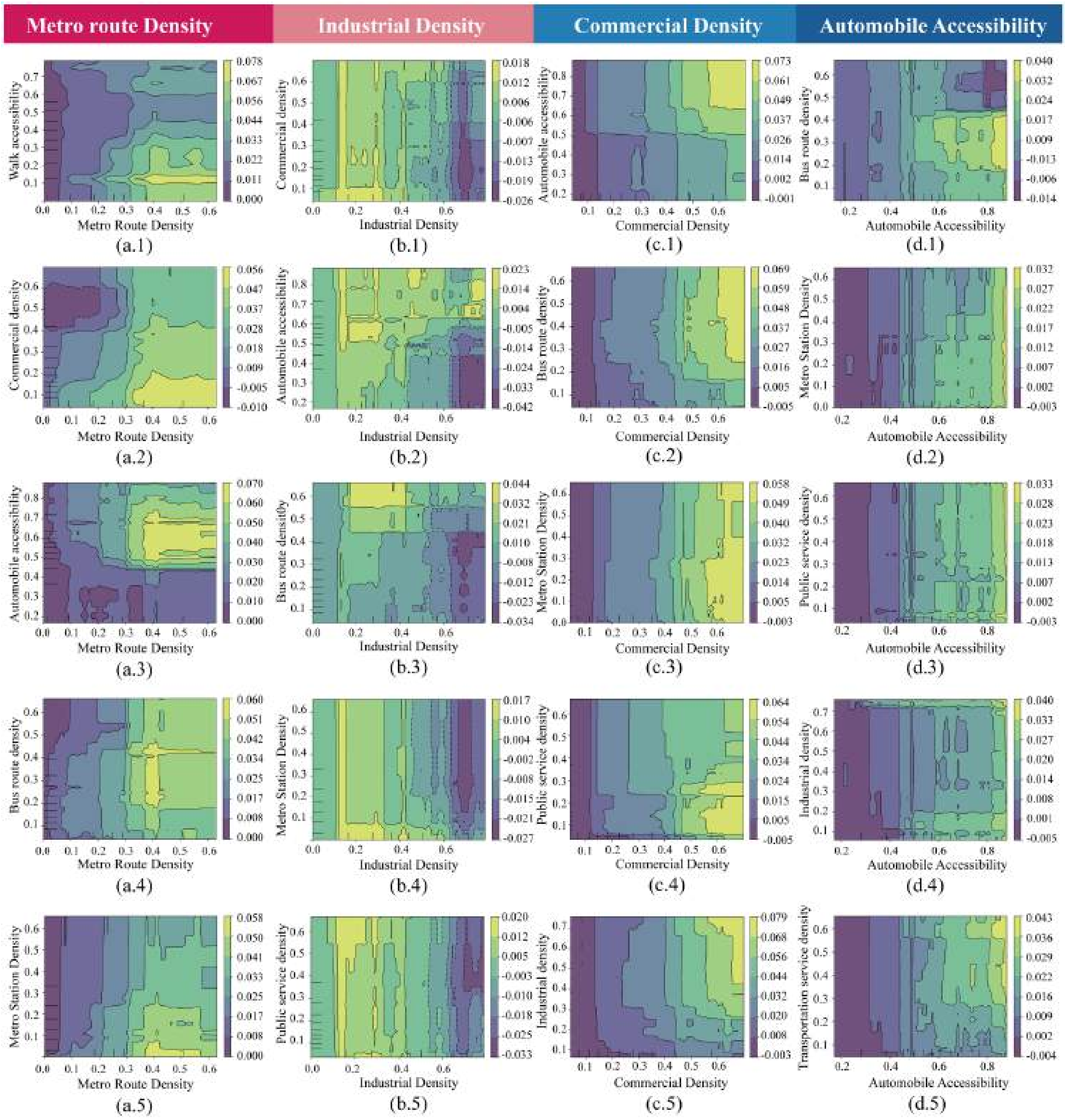

Fig. 8. Interaction plot of environmental variables in FSs in Partial Dependence Plots.

nodes, along with their prior probabilities and the influence of variable Z. The parent nodes of Z, which are variables X and Y, require conditional probabilities that account for their states. Since BNs typically handle discrete node states (Thomsen et al., 2016), variables need to be discretized into intervals prior to calculation.

As for *n* variables $X_1, X_2, \ldots, X_n$, the joint probability can be calculated through Eq. (14), in which *parent* (X_i) refers to the parent node of variable X_i. Assuming conditional independence, Eq. (15) can be further obtained, in which $P(V_j|D)$ refers to the posterior probability of V given D, $P(V_j)$ is the prior probability of V, $P(D|V_j)$ is the conditional probability when V_j is true, while the denominator is the total probability (Cai et al., 2018).

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P(X_i| \text{ parent } (X_i)) \tag{14}$$

$$P(V_j|D) = \frac{P(D|V_j)\cdot P(V_j)}{\sum_{i=1}^{n} P(D|V_i)\cdot P(V_i)} \tag{15}$$

Identifying nodes is a key step in modeling BN of residents' positive sentiments. According to Table 1, we have identified 4 nodes, namely street network, TOD, land use intensity, land use type, and streetscape perception. The subsystem includes a total of 21 main indicators, which are the outermost nodes in the network. The GeNIe modeler's syntax is used to represent the BN.

3. Results

3.1. The PSI in different urban settlements

We used NLP to conduct the PSI calculations on a dataset consisting of 135,650 text samples from FSs and UVs in Shenzhen. Our evaluation

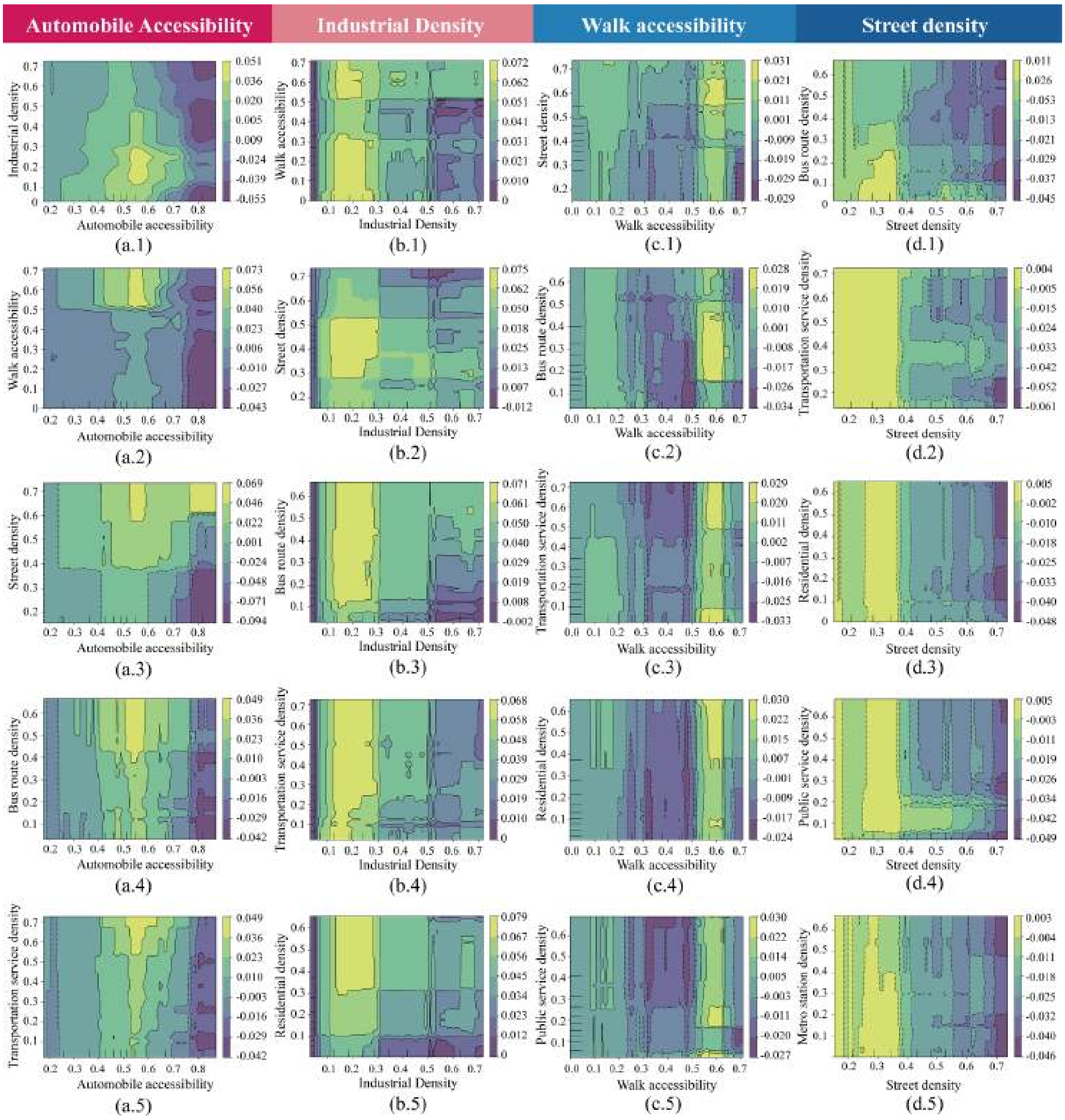

Fig. 9. Interaction plot of environmental variables in UVs in Partial Dependence Plots.

results showed that the NLP model achieved high precision (0.98) and recall (0.95) scores, indicating accurate identification of relevant sentiment values and capturing a significant proportion of actual sentiment values. The f1-score of 0.97 confirmed a statistically balanced performance between precision and recall.

The results indicated the mean PSI was 0.614 and 0.575 in FSs and UVs, respectively. The PSI is higher in FSs than in UVs in most administrative districts (except for Dapeng and Longhua) (Fig. 6a). Interestingly, the data revealed variations in the sentiment of people residing in different settlements within the same district, with Longhua showing the largest sentiment disparity, where the PSI is 0.209 higher in UVs than in FSs. Notably, the PSI exhibited significant spatial heterogeneity, displaying a medium-high-low trend from the city center to the suburbs. The mean PSI for urban center areas (Nanshan, Futian, and Luohu) was 0.6134, while the suburban regions represented by Longgang, Longhua, Yantian, and Bao'an showed a mean PSI of 0.647. The outlying suburbs (Pingshan, Guangming, and Dapeng) exhibited a mean PSI of 0.500. The highest and lowest values of the PSI for FSs occured in Longgang (0.709) and Dapeng (0.387), respectively. For UVs, the highest and lowest values of PSI were found in Longhua and Dapeng, with values of 0.733 and 0.394, respectively. However, we observed that aggregating PSI according to administrative districts did not yield significant patterns, as these districts used for urban management were not directly related to the SE and PSI. Therefore, we further examined the geographical distribution of the PSI.

Fig. 6b and c illustrated the geographical distribution of the PSI in FSs and UVs. We standardized the PSI and classified them into five clusters by natural breaks methods: low, medium low, medium, medium high, and high. High and low PSI values showed more obvious spatial clustering effects, whereas medium values tended to be more mixed in geographical distribution. In FSs, high PSI values were mainly concentrated in the center of Futian, the south of Nanshan, and the center of Longgang. Conversely, low values were mainly concentrated in the north-central part of Longhua, Dapeng, and the central part of Pingshan.

In UVs, high PSI values accumulate in a small number of areas in the north of Longhua and central Longgang, while low values are distributed in Dapeng, central Pingshan, northern Longgang, northern Bao'an, and Guangming. The distribution of the PSI in FSs and UVs showed minor differences in most districts. The districts with the largest sentiment disparities are concentrated in the urban fringes (northern Longhua, northeastern Longgang, and northern Nanshan). The spatial heterogeneity of the PSI breaked the inherent notion that residents in FSs have more positive sentiments than residents in UVs.

3.2. SHAP analysis

Based on the XGBoost, we conducted a SHAP analysis on the variables affecting residents' positive sentiments. SHAP analysis allows us to measure the importance variables contribute to the generation of PSI based on Shapley values (Fig. 7).

In Fig. 7a.1, the top three important variables in FSs which positively correlated with PSI were metro route density (SHAP value 0.013), walk accessibility (0.010) and commercial density (0.009). This implies that increasing metro density, walk accessibility and commercial density can promote positive sentiments in FSs. Other significant positive variables included metro station density and green space density. The SHAP importance of automobile accessibility and bus station density is 0.009 and 0.007, respectively, implying a negative impact on the PSI (In 2SFCA, the high accessibility value represents the low accessibility.) Other variables that exhibited negative effects included public service density and industrial density. However, the global importance of variables may not provide critical evidence at the local level. For instance, a negative correlation between bus route, bus station density and PSI may not be explained. To further elucidate these findings, we used the local feature importance plot (Fig. 7a.2). We found that when the importance value of bus density was less than 0 or greater than 0.02, it had a positive impact on the PSI. However, when the coefficient is between 0 and 0.02, it showed a negative correlation. Lower bus density fosters a positive sentimental state as it alleviates traffic congestion and promotes a healthier air environment. This phenomenon potentially relations to settlements with strong internal living and working circulation (further discussed in Section 4.3). Conversely, the presence of a high bus density (above 0.02) promotes the PSI owing to the convenience afforded by public transportation.

Fig. 7b.1 illustrated that automobile accessibility (SHAP value 0.176), street density (0.011), bus route density (0.011), and transportation service density (0.076) exhibited positive correlations with the PSI in UVs (Gao et al., 2019; Gao et al., 2021; Kanwal et al., 2020). Significantly, we found that important positive SE variables in UVs are all closely related to urban mobility and commuting of the mobile population in UVs, as reflected in transportation costs (bus station density) (Gao et al., 2019), social inclusion (automobile accessibility) (Gao et al., 2021), and community service amenities (transportation service) (Kanwal et al., 2020). Residents in UVs exhibited a positive sentiment when the street network was well-developed, easily accessible by car, and accompanied by robust bus routes and transportation infrastructure. In contrast to FSs, mobility-related SE variables within UVs underscored the significance of considering the diverse requirements of settlement populations as a vital consideration for urban planners in formulating tailored settlement planning strategies. Furthermore, the variables displaying a negative correlation with the PSI included industrial density and walk accessibility. This is due to the environmental pollution from industrial parks that affect SE and lead to negative sentiments (Yao et al., 2022). Moreover, as depicted in Fig. 7b.2, when the SHAP value of walk accessibility falls within the range of 0 to 0.025, there remains a positive relationship between walk accessibility and the PSI, indicating that short-distance walking generates positive sentiments. However, considering the expansive size of Shenzhen and the availability of other transportation models, the choice of long-distance walking is clearly not realistic nor conducive to promoting positive sentiments.

Our joint analysis of global and local feature importance provided insights into the positive and negative relationships between variables and the PSI. Nevertheless, to further explore the synergy between multivariate, we utilized PDPs to examine the interactions among variables and the nonlinear relationship between multivariate and the PSI.

3.3. Partial Dependence Plot analysis based on XGBoost

After analyzing the SE variables that significantly contribute to the PSI, we narrowed down our selection to the top four ranked variables. We employed two-way PDP analysis to identify nonlinear relationships between multiple variables. The PDP analysis is demonstrated to help identify the optimal solution interval between the two variables for promoting the PSI. The dark blue interval is the target interval, reflecting the minimum peak flow, while the yellow interval is the warning interval, reflecting the maximum peak flow (see Figs. 8 and 9). We standardized all variables before the PDP analysis.

Fig. 8 depicted the key variables that contribute to the PSI in FSs. Based on the SHAP analysis, we have selected metro route density, industrial density, commercial density, and automobile accessibility for the PDP analysis. We found a strong positive relationship between metro route density and the PSI (Figs. 8a.1 to a.5), indicating that public transportation accessibility played a critical role in influencing the PSI of FS residents. Notably, high pedestrian accessibility and low automobile accessibility were identified to contribute positively to the PSI. This suggests a preference among FS residents for pedestrian-friendly spaces while being less exposed to automobile-oriented areas. These findings are consistent with previous studies (Rebecchi et al., 2019). The results of Figs. 8b.1 to b.5 were consistent with the SHAP results, demonstrating the negative effect of industrial density on the PSI. Thus, it is recommended that planners consider maintaining a significant distance between residential areas and industrial zones while striving to minimize environmental pollution and noise levels to the fullest extent possible. The positive contribution of commercial density to the PSI was evident in Figs. 8c.1 to c.5. Increased bus route density, along with a higher commercial density and reduced automobile accessibility, can significantly enhance the PSI. This indicates that public transport convenience is more desirable than automobile access for FS residents (Kanwal et al., 2020). The same conclusion is supported by Fig. 8d.1 to d.5.

Fig. 9 presented the significant SE variables that contribute to the PSI in UVs. We selected automobile accessibility, industrial density, walk accessibility, and street density. The findings depicted in Figs. 9a.1 to a.5 reveal that a moderate level of automobile accessibility (standardized coefficient between 0.5 and 0.6) meets the sentimental expectations of UV residents, corroborating the SHAP analysis. On one hand, UV residents with lower automobile accessibility (below 0.5) may choose public transportation alternatives. This is evidenced by Figs. 9a.4 and a.5 that higher density of bus routes (above 0.4) and transportation facilities (above 0.5) promotes the PSI. On the other hand, a high level of automobile accessibility (above 0.6) necessitated the provision of additional facilities such as parking, further intensifying the dense living spaces within UVs.

Figs. 9b.1 to b.5 showed that, similar to FS, increased industrial density is not conducive to positive sentiments among UV residents. However, lower walk accessibility is more likely to promote the PSI (Figs. 9c.1 to c.5). Given the remote locations of certain UVs and the expansive size of Shenzhen, it poses a challenge for urban villagers to rely on walking to reach their destinations (Pan and Du, 2021). The PDP analysis of walk accessibility and automobile accessibility revealed that bus route density, street density, and transportation service density were positively correlated with the PSI. This implied that UV residents, who are predominantly mobile, prefer to use public transportation facilities to reduce travel costs. This finding is consistent with the results presented in Fig. 7b.1.

A negative correlation and a threshold effect were identified between

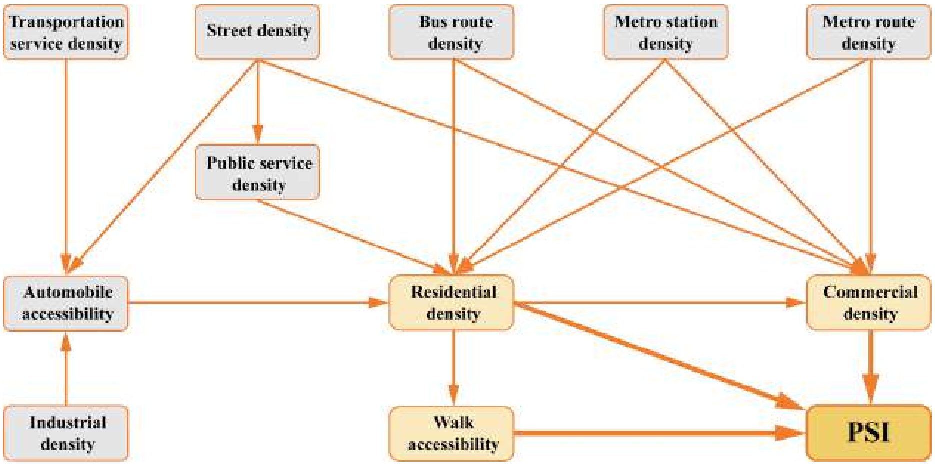

Fig. 10. Schematic illustration of the ISM structure.

street network density and the PSI (Figs. 9d.1 to d.5). Residents in marginalized UVs characterized by low-density streets exhibited a heightened positive sentiment. This may be influenced by lower housing prices and other socioeconomic reasons. In these UVs, the density of transportation facilities such as bus route density and metro station density has only a weak negative correlation with the PSI. We indicated that a highly close-loop community economies and self-management policies, exemplified by e-commerce, positively impact the PSI in these UVs. These findings align with previous studies on the integration of UVs and the e-economy, where the online trade and e-ecommerce has influenced the SE and residents' lives in UVs (Lin, 2019; Tang and Zhu, 2020a; Tang and Zhu, 2020b). Further identification regarding these specific UVs is provided in the discussion section.

3.4. Model configuration and structure based on ISM and BN

Section 3.3 highlighted the significant contribution of variables to the PSI and the interplay between multiple variables. Nonetheless, implementing these findings in settlement planning presents a challenge given the complexity of nonlinear relationships. Bayesian principles offer significant advantages in inferring events with uncertain relationships, as they align with people's cognitive laws (Kabir and Papadopoulos, 2019). Given the complex and diverse interactions among the SE variables in assessing the PSI, we adopted BN for its assessment and validation. Combining ISM and BN into one assessment framework may provide a more reliable analysis.

We selected 12 key variables based on SHAP results, represented by A1...A12, corresponding to street density, walk accessibility, bus route density, metro station density, residential density, commercial density, industrial density, public service density, transportation service density, automobile accessibility, metro route density, and the PSI. Table A 2 showed the adjacency matrix, which represents the associations between elements and was derived from experts' experience and logical judgments. In the matrix, "0″ indicates no association between nodes, while "1″ indicates an influence. Table A 3 represented the reachable matrix, which indicated the reachability or accessibility of elements in the system. This matrix indicates whether one element can be reached from another element by following a path of direct or indirect influence. A value of "1″ in the matrix indicates that the corresponding element can be reached from the element in the corresponding row, while a value of "0″ indicates that the element is not reachable.

The hierarchical decomposition process of the model was demonstrated in Table A 4. During each extraction, if the intersection of the reachable set and the intersection set is determined to be consistent, the set of elements can be extracted for hierarchical decomposition. This operation is repeated until the hierarchy of all elements is determined, so that the hierarchy of each element can be obtained: ***Level 1***= (PSI), ***Level 2***= (walk accessibility, commercial density), ***Level 3***= (residential density), ***Level 4***= (bus route density, metro station density, public service density, automobile accessibility, metro route density), ***Level 5***= (street density, industrial density, transportation service density).

The hierarchical division of ISM represents the most straightforward topology in the PSI influence variable system. Fig. 10 depicted the hierarchical structure, reflecting the process and mechanism by which the SE variables influence the PSI. To mitigate the influence of different units and ranges of SE variables, the variables were discretized into multiple intervals to improve computational efficiency and ensure consistency. All variables were standardized, and the natural discontinuity method was used for classification (Table A 5).

A total of 55,292 sets of spatial data were input to the Netica for parameter learning (Fig. 11). The resulting model consisted of 12 nodes, with the PSI node having two states (Y/N), and all other nodes having five states based on the classification in Table A 5. The probabilities of each state were determined using historical data, and the prior and conditional probabilities of each node's attributes were also taken into account.

BN allows all nodes to function as either evidence or targets, with both types requiring a calculated value of at least 1. The accuracy of target node calculation increases with more evidence nodes incorporated into the network. For this study, PSI nodes serve as targets, with three direct nodes and eight indirect nodes. When the direct nodes function as evidence, the indirect nodes lose their ability to influence the PSI. However, when the direct nodes remain unknown, the indirect nodes become crucial in the derivation process.

3.5. Validation of the PSI evaluation

We conducted a validation of probabilistic results of the PSI using raw data from FS and UV input to BN. The validation results informed the standardization and classification of the PSI using the natural interval method, with identical values employed to ensure comparability. In contrast to previous studies (Li et al., 2023), we did not utilize kriging interpolation or inverse distance weighting for large-scale visualization due to the potential duplication of FS and UV values. Instead, we utilized a hexagonal fishing net as the minimum study unit. As illustrated in Figs. 12a and c, the predicted PSI values closely align with the true value

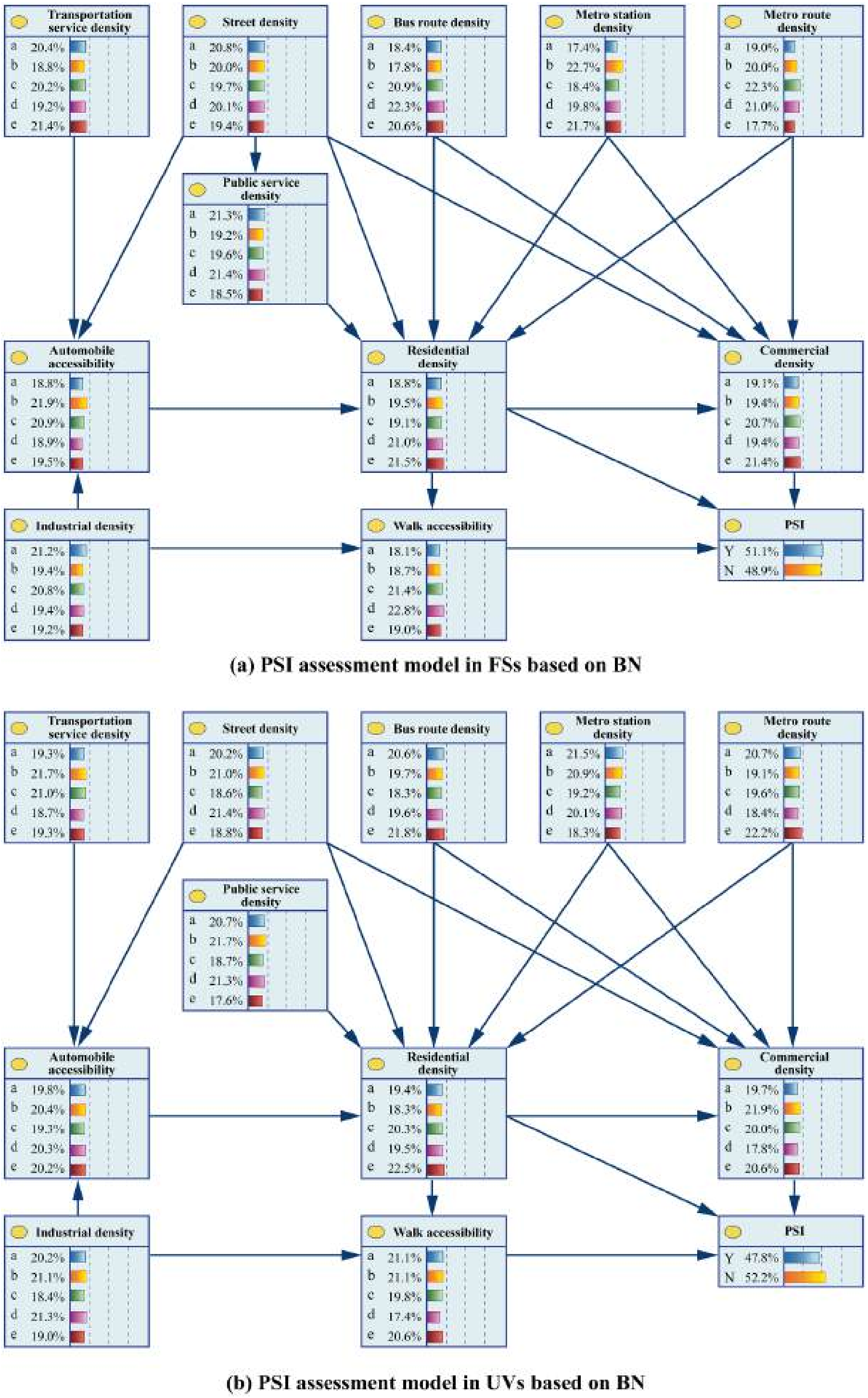

Fig. 11. PSI assessment model in FSs and UVs based on BN. (a) PSI assessment model in FS based on BN, and (b) PSI assessment model in UVs based on BN.

of the PSI.

In FSs, a PSI above 0.515 indicated a positive sentiment, while in UVs, a value higher than 0.556 denoted a positive sentiment. However, the thresholds for PSI prediction differ, with the model classifying a "Y" status when the predicted result is above 50%, and vice versa. According to validation results, the model achieved an accuracy of 77.5% in evaluating the PSI. Additionally, the resulting Receiver Operating Characteristic (ROC) curve yields an Area Under ROC Curve (AUC)

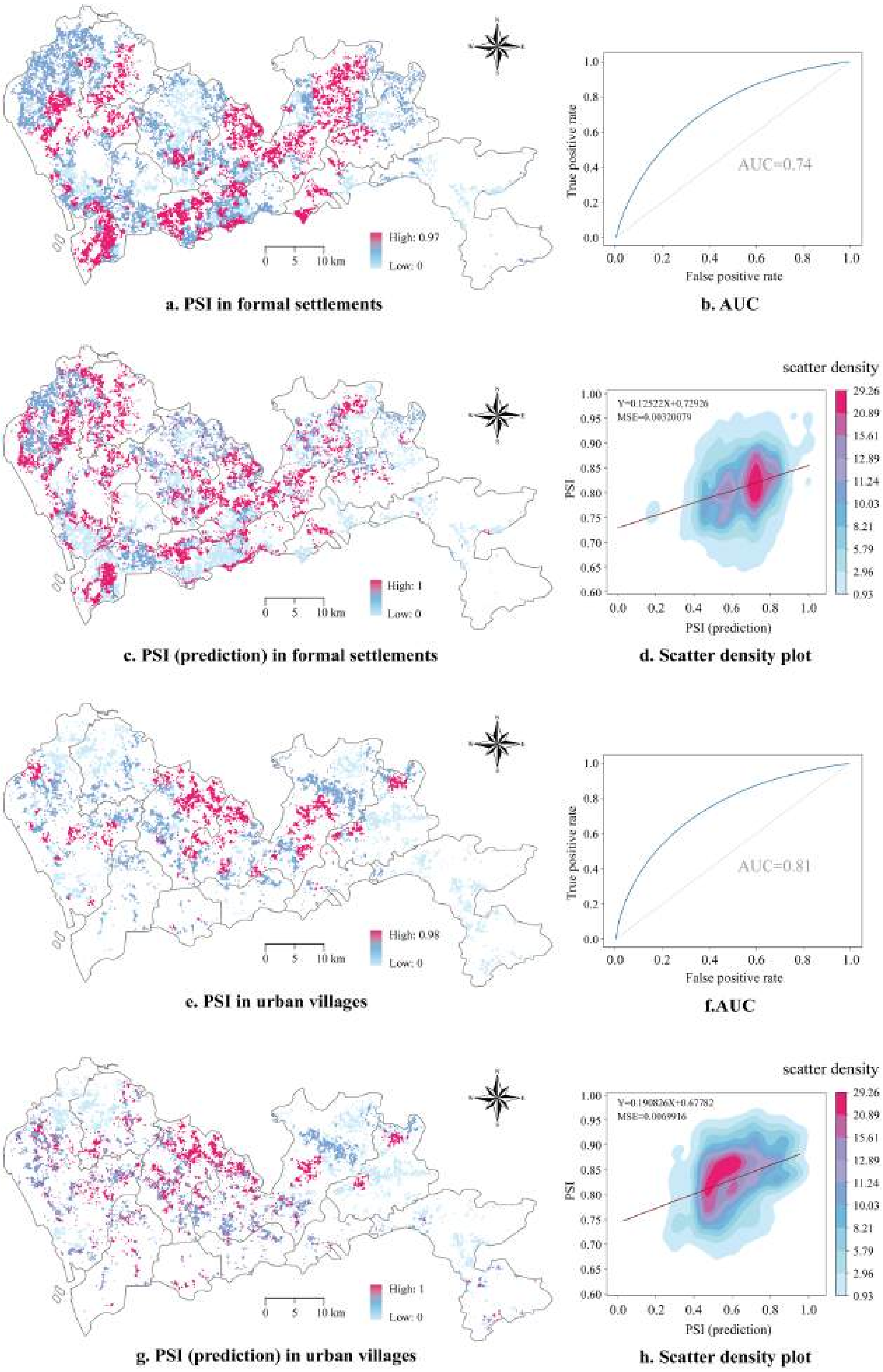

Fig. 12. Comparisons of PSI and predicted PSI in FSs and UVs. (a) PSI in FSs, (b) AUC, (c) PSI prediction in FSs, (d) scatter density plot, (e) PSI in UVs, (f) AUC, (g) PSI prediction in UVs, and (h) scatter density plot.

value of 0.74 in FS and 0.81 in UV, as depicted in Figs. 12b and f, respectively. The AUC ranges from 0.5 to 1, where 0.5 indicates that the model performs no better than random classification results, while 1 indicates that the model is a perfect classifier. Fig. 12d and h demonstrated that the linear fit of PSI predicted values to the true values at FS and UV, respectively, yields a mean square error (MSE) of 0.0032 and 0.0070. Therefore, the PSI inference based on ISM-BN produces reasonable results and boasts high accuracy.

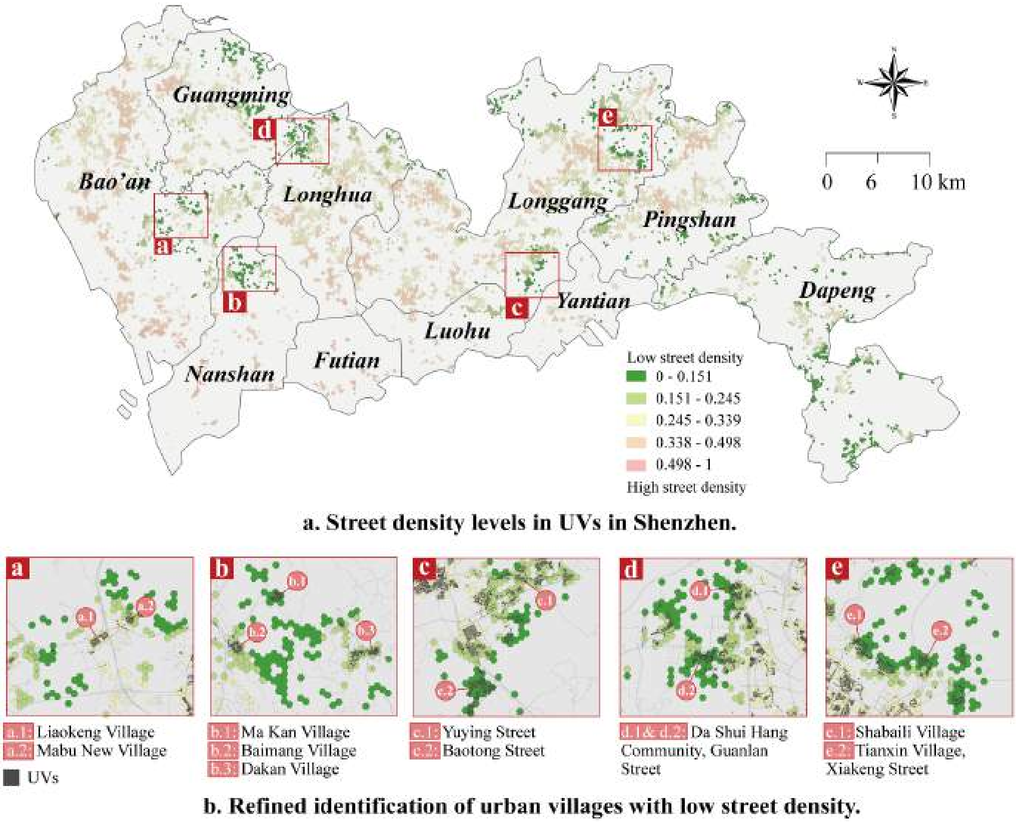

Fig. 13. Identification of UVs with low street density. (a) Street density levels in UVs in Shenzhen, and (b) refined identification of UVs with low street density.

Table A1
The comparison of evaluation results of different machine learning models.

Machine learning models	Training data set				Testing data set			
	MSE	RMSE	MAE	MAPE	MSE	RMSE	MAE	MAPE
Decision tree	0.001	0.031	0.024	3.057	0.011	0.105	0.095	12.352
Radom forest	0.001	0.028	0.022	2.924	0.01	0.102	0.095	12.15
Support vector machine	0.004	0.061	0.053	7.128	0.021	0.143	0.14	18.991
XGBoost	0.001	0.005	0.003	0.402	0.009	0.097	0.088	11.298

4. Discussion

4.1. The common SE variables affecting the PSI in all settlements

In the results section, we addressed the first research question: How do diverse SE variables impact residents' positive sentiments? Building upon this, Section 4 responds to the subsequent research question: What measures should be undertaken to enhance the SE to foster residents' positive sentiments? We first discussed SE variables that are generally applicable to FSs and UVs. Moreover, Sections 4.2 and 4.3 present differentiated planning recommendations to different settlements.

For FSs and UVs, it was found that industrial density was negatively associated with sentiments in all settlements. This is due to the pollution caused by industrial parks, which affects the SE and results in residents'

Table A2
The adjacency matrix of the variables influencing the PSI.

Variables	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
A1	0	0	0	0	1	1	0	1	0	`	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	1
A3	0	0	0	0	1	1	0	0	0	0	0	0
A4	0	0	0	0	1	1	0	0	0	0	0	0
A5	0	1	0	0	0	1	0	0	0	0	0	1
A6	0	0	0	0	0	0	0	0	0	0	0	1
A7	0	0	0	0	0	0	0	0	0	1	0	0
A8	0	0	0	0	1	0	0	0	0	0	0	0
A9	0	0	0	0	0	0	0	0	0	1	0	0
A10	0	0	0	0	1	0	0	0	0	0	0	0
A11	0	0	0	0	1	1	0	0	0	0	0	0
A12	0	0	0	0	00	0	0	0	0	0	0	0

Table A3
The reachable matrix of the variables influencing the PSI.

Variables	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
A1	0	0	0	0	1	1	0	1	0	`	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	1
A3	0	0	0	0	1	1	0	0	0	0	0	0
A4	0	0	0	0	1	1	0	0	0	0	0	0
A5	0	1	0	0	0	1	0	0	0	0	0	1
A6	0	0	0	0	0	0	0	0	0	0	0	1
A7	0	0	0	0	0	0	0	0	0	1	0	0
A8	0	0	0	0	1	0	0	0	0	0	0	0
A9	0	0	0	0	0	0	0	0	0	1	0	0
A10	0	0	0	0	1	0	0	0	0	0	0	0
A11	0	0	0	0	1	1	0	0	0	0	0	0
A12	0	0	0	0	00	0	0	0	0	0	0	0

Table A4
The intersection between reachable and antecedent sets.

Variables	The reachable set	The intersection set
A1	A1, A2, A5, A6, A8, A10, A12	A1
A2	A2, A12	A2
A3	A2, A3, A5, A6, A12	A3
A4	A2, A4, A5, A6, A12	A4
A5	A2, A5, A6, A12	A5
A6	A6, A12	A6
A7	A2, A5, A6, A7, A10, A12	A7
A8	A2, A5, A6, A8, A12	A8
A9	A2, A5, A6, A9, A10, A12	A9
A10	A2, A5, A6, A10, A12	A10
A11	A2, A5, A6, A11, A12	A11
A12	A12	A12

dissatisfaction. This inference is supported by the sample text: 'the air carries an unpleasant smell of sewage due to non-compliance with sewage treatment in nearby parks.' Therefore, settlement planning must prioritize reducing the density of surrounding industrial parks while maintaining a safe distance to avoid any adverse effects on the SE.

Moreover, we suggest that urban planners prioritize the development of public transportation services (bus and metro) while decreasing the priority of automobile accessibility in all settlements. By this means, we can create a safer environment and promote active travel and the use of public transportation. Besides, this approach could reduce the occupation of scarce public space in UVs (fewer parking lots), ensuring residents' outdoor activities and commuting.

4.2. Planning recommendations for FSs

In planning FSs, increasing metro facilities should be prioritized to improve residents' commuting experience. The construction of a metro route has been found to be highly correlated with the positive sentiment of residents. This correlation can be attributed to the fast and reliable transportation provided by the metro, which helps alleviate traffic congestion and reduce commuting time (D'Orso and Migliore, 2020).

Increasing the commercial density around FSs is essential for providing social and employment opportunities while creating a sense of community belonging (Gehl, 2013; Shaolian, 2017). FS residents, who are less mobile than those in UVs, can benefit from the availability of commercial facilities nearby. PDP analysis showed that higher commercial density, developed bus routes, and reduced automobile accessibility are positively correlated with residents' sentiment in FSs. In response to SDG 11 "good health and well-being" (UN, 2015), our planning suggestions highlight the importance of commercial areas around FSs in promoting healthy communities (Mehta, 2007).

Promoting walkable neighborhoods and reducing automobile access are crucial for creating walkable, convenient, and safe "15-minute community life unit," as proposed in the "*Spatial Planning Guidance: Community Life Unit*" (Ministry of Natural Resources, 2021). Studies have shown that higher walkability can motivate residents to commute by active travel, while lower auto accessibility can decrease private car usage, leading to less air pollution, noise, and traffic congestion (Rui and Othengrafen, 2023; Talen et al., 2013). These factors contribute to the physical and mental well-being of residents (SDG 11) (UN, 2015; Zhang et al., 2020).

4.3. Planning recommendations for UVs

In contrast to FSs, planning authorities should differentiate planning solutions for UVs. Special attention should be given to marginalized UVs due to their unique contributions to urban economies and informal housing markets (due to low rental price). We identified the marginalized UVs through the threshold effect of street network density, which revealed a lack of special demand for transportation facilities such as metro and bus. The reason is that the high land price resulting from high-

Table A5
Discretization of influencing variable ranges for the PSI assessment.

Variables	Probability (%)									
	a		b		c		d		e	
	FS	UV	FS	UV	FS	UV	FS	UV	FS	UV
Transportation service density	0–0.15	0–0.159	0.15–0.27	0.159–0.313	0.27–0.421	0.313–0.479	0.421–0.614	0.479–0.692	0.614–1	0.692–1
Street density	0–0.248	0–0.216	0.248–0.374	0.216–0.355	0.374–0.501	0.355–0.493	0.501–0.688	0.493–0.651	0.688–1	0.651–1
Bus route density	0–0.156	0–0.139	0.156–0.291	0.139–0.276	0.291–0.444	0.276–0.428	0.444–0.641	0.428–0.61	0.641–1	0.61–1
Metro station density	0–0.159	0–0.102	0.159–0.322	0.102–0.276	0.322–0.488	0.276–0.447	0.488–0.693	0.447–0.668	0.693–1	0.668–1
Metro route density	0–0.102	0–0.103	0.102–0.226	0.103–0.276	0.226–0.373	0.276–0.455	0.373–0.602	0.455–0.663	0.602–1	0.663–1
Public service density	0–0.127	0–0.139	0.127–0.245	0.139–0.286	0.245–0.399	0.286–0.453	0.399–0.61	0.453–0.66	0.61–1	0.66–1
Automobile accessibility	0–0.254	0–0.265	0.254–0.443	0.265–0.432	0.443–0.586	0.432–0.583	0.586–0.763	0.583–0.765	0.763–1	0.765–1
Industrial density	0–0.186		0.186–0.343		0.343–0.507		0.507–0.688		0.688–1	
Residential density	0–0.127	0–0.111	0.127–0.253	0.111–0.251	0.253–0.415	0.251–0.43	0.415–0.622	0.43–0.636	0.622–1	0.636–1
Commercial density	0–0.147	0–0.117	0.147–0.279	0.117–0.25	0.279–0.439	0.25–0.404	0.439–0.649	0.404–0.593	0.649–1	0.593–1
Walk accessibility	0–0.219	0–0.248	0.219–0.391	0.248–0.417	0.391–0.555	0.417–0.575	0.555–0.729	0.575–0.763	0.729–1	0.763–1
PSI	0–0.515	0–0.556	0.515–1	0.556–1						

density street network is contrary to the daily needs of residents in marginalized UVs.

We identified UVs with low street network density using the natural interruption method based on the threshold effect in Fig. 9d. Fig. 13a illustrated the identification of UVs with low street network density. Specifically, areas a, b, and c are located in the peri-urban region, while area d and e are situated in the distant suburbs. Fig. 13b provided a closer view of these identified areas and included a list of the corresponding UVs. These UVs exhibit cost-effective settlements and work environments, which form a foundation for the emergence of innovative economic models. With the rise of the e-commerce economy, cities like Shenzhen have witnessed the combination of e-commerce and villages (Wang et al., 2021a). Marginalized UVs, characterized by high labor density and low rental costs, have become breeding grounds for e-trade (Lin et al., 2016; Shi et al., 2021). The government encourages this cheap and efficient economic model by proposing "one village one product" (Natsuda et al., 2012) to improve the economic competitiveness of different districts. Therefore, planning authorities must ensure the diversity of urban settlements and preserve the unique identity of marginalized UVs. These highly closed-loop "small special economic zones" can secure livelihoods for low-income groups and are strategically significant for community harmony and socioeconomic transformation of UVs (Miao and Phelps, 2019; Wang et al., 2021a).

In contrast to FSs, we recommend that the planning department prioritize walk accessibility at the micro scale over the macro scale when planning for UVs. The internal network in UVs primarily consists of alleys and streets, which are well-connected and impede access by cars, resulting in a high proportion of walkability. However, at a macro level, UVs are situated in more remote urban edges than FSs, posing challenges for UV residents to reach their travel destinations solely by walking. Improving the walkability of UVs at the city level, such as enhancing the street network, has the potential to enhance the overall value of UVs. While it may enable landlords to capitalize on increased profits (Jiang et al., 2020), it simultaneously raises the cost of living for the predominant demographic of UV residents—the floating population (Hao et al., 2011). Consequently, UVs run the risk of losing their inherent advantage of providing affordable housing. This particularly compromises the competitiveness of marginalized UVs in the realm of e-commerce (Lin, 2019; Shi et al., 2021). Such strategies are incongruous with the pursuit of sustainable communities outlined in SDGs 11 (UN, 2015).

4.4. Research contributions

In line with previous research, our study demonstrates that well-designed SEs play a crucial role in shaping residents' positive sentiments (Dong and Qin, 2017; Helbich, 2018).

At the theoretical level, previous studies that have utilized social big data as a response variable have primarily focused on urban parks and green spaces (Guo et al., 2022; Kong et al., 2022a; Wang et al., 2021b). However, studies that examine SEs often do not differentiate between settlement types (Turley et al., 2013b). In addition, few studies that focus on slums cannot be effectively compared to settlements due to their distinct economic, social, and geographical attributes (Turley et al., 2013a). To fill this gap in fine-grained classification in current settlement studies, we identified and compared FSs and UVs in Shenzhen. Moreover, this study is relevant given the increasing development of UVs in China's large cities and the introduction of government policies on UV transformation.

Previous studies on SEs have utilized participant scoring or geographically weighted regression using GIS (Nordbø et al., 2018). In contrast, our study employed machine learning techniques, which provided an objective experimental outcome by avoiding the potential subjective component of the scoring process. We employed PDP analysis, which not only strengthens the significance of our SHAP study, but also highlights the advantages of machine learning in dealing with the complexity of variables. Specifically, the street density thresholds demonstrated by our PDP results provided valuable insights into the intricate interplay of SE variables and their potential implications for urban planning (Figs. 9d and 13). Additionally, given that SE variables often involve both numerical and logical relationships, we constructed a framework of key variables using the ISM approach and validated it using BN. The results demonstrated the validity of our selected SE variables and complement the underlying logical relationships in addition to the numerical basis. These findings bear important implications for urban planning, as they offer a more comprehensive and nuanced understanding of SEs and their dynamics.

At the policy level, our study presented a differentiated settlement plan in response to China's latest "*New Urbanization Implementation Plan during the 14th Five-Year Plan period (2021–2025)*" (National Development and Reform Commission, 2022). It aligned with the "*Shenzhen Urban Village Comprehensive Improvement Plan (2019–2025)*" issued by Shenzhen Planning & Natural Resources Bureau (2019). In particular, we offered settlement planning recommendations aimed at fostering a secure, inclusive, and harmonious living environment, aligning with the objectives outlined in the "*Spatial Planning Guidance: Community Life Unit* (Ministry of Natural Resources, 2021)." Moreover, this study presented a comprehensive classification and management framework for settlements that supports the current UV renewal policy, emphasizing the shift from "mass demolition" to "refinement" (Shenzhen Planning & Natural Resources Bureau, 2019).

4.5. Research limitations and further directions

First, the composition of Weibo users in settlements primarily comprising teenagers may not provide a representative sample of all residents (Duan et al., 2022). Further research should incorporate diverse data sources such as street images, questionnaires, and self-reported sentimental state data. Second, we used a grid with a 100 m side length to identify the geographic location of different settlements. However, it is challenging to demonstrate spatial autocorrelation and spatial heterogeneity using GWR models because smaller study units may not reflect the true values of independent variables and may have covariance issues. Thus, future studies could consider alternative methods to reveal the geographical correlations. Third, our findings revealed the impact of SE on the PSI. Nevertheless, it is crucial to acknowledge that residents' sentiments are influenced by various variables, including work, family, and economic conditions (Melton, 2018), and may exhibit varying results over time. Hence, shaping healthy and sustainable communities require a comprehensive and multidisciplinary approach that goes beyond improving the settlement environment.

5. Conclusion

This study utilized NLP (BERT model) and multiple machine learning algorithms to analyze social media data and establish a logical framework for SE variables affecting positive sentiment in Shenzhen. The framework was validated using BN and achieved an AUC of 0.74 and 0.81 for FSs and UVs, respectively. The sentiment map exhibited significant spatial heterogeneity in the PSI, with a medium-high-low trend from the city center to the suburbs.

In regard to all settlements, our study proposed a planning recommendation to decrease the density of industrial zones surrounding these settlements. Simultaneously, we emphasized prioritizing public transportation while reducing the automobile access to settlements. By implementing these measures, we can foster the development of safe, eco-friendly, and sustainable communities in alignment with the SDGs (UN, 2015). Furthermore, distinct planning proposals were being put forth for FSs and UVs. For FSs, recommendations included increasing metro facilities and commercial density, building walkable neighborhoods, and reducing automobile access. For UVs, differentiated planning strategies were recommended that emphasizes maintaining low street density in marginalized UVs for e-commerce while de-prioritizing the macro-level transformation of UV walkability.

The study highlighted the importance of fine-scale identification of settlements with mixed sentiment scores to provide specific planning suggestions. Ultimately, these recommendations can lead to positive transformation and foster community cohesion in FSs and UVs in Shenzhen.

CRediT authorship contribution statement

Jin Rui: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rui Jin reports financial support was provided by China Scholarship Council.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104851.

Appendix

Tables A1, Tables A2, Tables A3, Tables A4, Tables A5.

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Article 4: Key facts and author contributions

Reference	Rui, J. (2024). Exploring the nonlinear association between street vitality and physical street environment in urban villages: using deep convolutional neural network and deep learning techniques
Contributions	RJ: 100%
History	Submitted: 10 April 2024

Signature:

Jin Rui

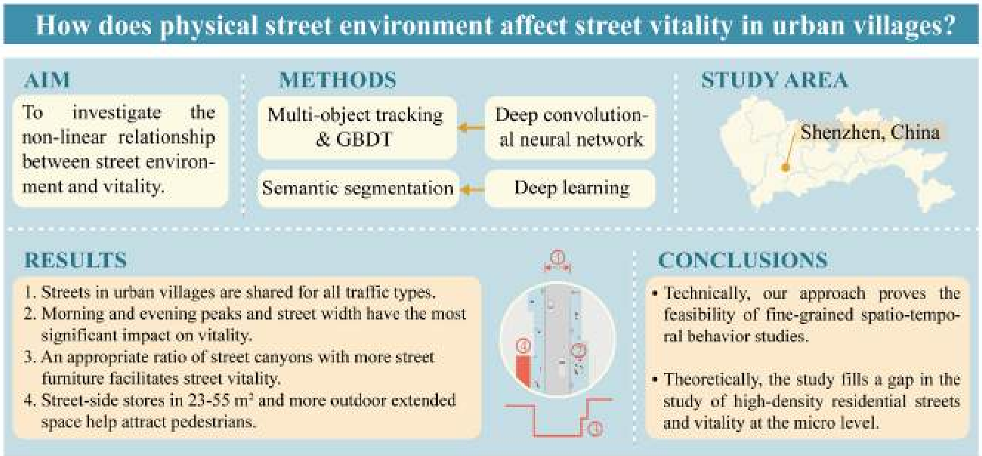
Date

Exploring the nonlinear association between street vitality and physical street environment in urban villages: using deep convolutional neural network and deep learning techniques

Highlights

- A quantitative measurement based on DCNN and deep learning techniques
- Proposing a novel method combing semantic segmentation and multi-object tracking
- Elaborating association of micro-level environment with street vitality by GBDT
- Providing practical street renovation recommendations for current urban plans

Graphical Abstract



Abstract

With the progress of urban renewal, efforts to promote high degrees of street vitality have become prevalent in Chinese cities. Residential streets, especially in high-density urban settings, play a significant role in spatial vitality. Nevertheless, exploring the association between the physical environment of high-density residential streets and spatial vitality remains challenging. The study focuses on Baishi Zhou village, an urban village in Shenzhen, and employs a deep convolutional neural network (DCNN) to quantify the relationship between street environment and vitality. First, we used the drone to collect street videos manually and evaluated the spatio-temporal distribution of pedestrian flow during the day. Street vitality values were calculated through multi-object tracking and semantic segmentation. Then we derived the corresponding environmental variables through field research, semantic segmentation, and geographic analysis. Finally, a nonlinear regression model based on gradient-boosting decision trees (GBDT) was applied to elaborate on the effect of the physical street environment on vitality. The findings reveal the high inclusivity of urban village streets and the spatial heterogeneity of vitality across street types. The GBDT illustrates the vitality-boosting potential of different element combinations. Overall, this innovative approach advances fine-grained spatio-temporal behavior studies. It offers practical recommendations for street renovation to support the

ongoing urban village redevelopment planning of the government.

Keywords: street vitality, high density residential street, pedestrian flow, multi-object tracking, semantic segmentation, gradient boosting decision trees (GBDT)

1. Introduction

Since China's reform and opening, urbanization has been in full swing. However, urban planning authorities and designers in China prioritized economic growth over urban vitality and residential life when shaping urban space, resulting in low-quality and disordered urban sprawl (Lai et al., 2021; Yi et al., 2017). This paradigm makes the cities lack diverse, high-quality public spaces that negatively affect urban dwellers' health, well-being, and social cohesion (Mouratidis and Poortinga, 2020; Zhang et al., 2021). In recent years, with rising income levels and increasing demands for livability, the public has begun to expect high-quality and accessible public space for socializing, commuting, and entertainment (Song et al., 2016a). The Shenzhen Planning and Natural Resources Bureau released the "*Shenzhen Urban Village Comprehensive Improvement Master Plan (2019-2025)*" with the aim of governing and transforming urban villages. In line with China's latest "*new urbanization implementation plan during the 14th Five-Year Plan period (2021-2025)*", our study seeks to enhance the quality of micro-street environments and promote spatial vitality in urban villages. The study provides valuable planning recommendations for urban village redevelopment to support this endeavor.

Jacobs (1961) proposed the concept of urban vitality as a catalyst for diverse social activities in public spaces to improve residents' quality of public life. Urban vitality can accelerate social cohesion through increased interaction potential and efficiency and is therefore increasingly considered by scholars as an essential evaluation indicator for developing livable cities (Maas, 1984; Mouratidis and Poortinga, 2020). With the growing demands for urban spatial quality and livability, the literature on urban studies has paid greater emphasis on developing higher levels of urban vitality. Scholars believe that urban vitality can be understood as a kind of urban activity based on the form of urban space (Li et al., 2022) and quantified by assessing the type and frequency of human activities in the space, including commuting, recreation, and social activities (Gehl, 1987; Li et al., 2022). It is worth emphasizing that the street plays a crucial role in promoting the vitality of public space; therefore, examining the correlations between urban street vitality and the physical street environment is of great significance (Gehl et al., 2006; Jiang et al., 2022; Montgomery, 1998). Relevant research on how the built environment of streets causes and promotes urban vitality can be traced back to the 1960s (Jacobs, 1961). However, the existing evidence has yet to succeed (Ye et al., 2017). One primary reason is that previous studies used personal observation to assess spatial vitality (Gehl et al., 2006), which is time-consuming and difficult to achieve large-scale and high-precision investigation. Moreover, most macro-scale studies have evaluated a single variable for its influence on spatial vitality, such as urban mobility (Sulis et al., 2018) and block size (Long and Huang, 2019), and it is difficult to reflect the underlying factors comprehensively. Some studies have examined the effects of multiple factors on vitality, such as block density and typology (Ye et al., 2018) and street width greenery, openness, and transparency (Li et al., 2022). All of them have employed linear-based regression models or hierarchical multiple regression models. However, the complex variables of the street environment rarely exhibit simple linear associations, making it challenging to capture variable dependencies and bivariate contributions between variables. In short, there is an urgent need for reliable tools for street vitality measurement and related influencing variables, as well as frameworks and automation to improve replicability.

The recent growth in deep learning and big data technology has brought about a paradigm shift in measuring urban environments and street vitality (Dong et al., 2021; Sulis et al., 2018). The increasing popularity of urban geographical information system (GIS) data, crowdsourcing data, and point of interest (POI) facilitate the acquisition of basic information on urban streets environment for urban planners and researchers, allowing for large- and fine-scale spatial measurements. Semantic segmentation based on deep learning algorithms helps to identify the sky, trees, buildings, and other facilities in the street and be used for perceptual analysis and urban canyon classification (Hu et al., 2020; Ma et al., 2021; Qiu et al., 2021). Simultaneously, the development of DCNN has enabled multi-target tracking approaches to detect pedestrian behavior, motion, and preferences (Donaire et al., 2020; Kim, 2020). Combined with video-based surveillance to record people's activity data, people in a common area can be counted and gridded to offer a new way to track and quantify how space is used (Hou et al., 2020). Inspired by these new technologies, this paper aims to provide a new perspective for measuring street vitality and its related built environment features in high-density cities in Shenzhen. We combined DCNN-based multi-object tracking and semantic segmentation with deep learning-based Gradient boosting decision trees (GBDT) to detect and elaborate their associations.

Shenzhen, the fastest-expanding city in China within the last 30 years, is one of the major hubs of China's economic growth (Hin and Xin, 2011). Rapid urban expansion results in conflict between new cities and old settlements, which gives rise to high-density urban villages. In contrast to other communities, urban villages as informal settlements become livable due to their central position, inexpensive rents, extensive employment possibilities, and diverse land use patterns (Pan and Du, 2021). Baishizhou village in Nanshan district, Shenzhen, was chosen as our study area. It is situated along a metro line in a densely populated urban area. Its crowded neighborhood environment replicates residents' daily lives in the high-density metropolitan districts of the Pearl River Delta, offering great opportunities to study street vitality.

The objective of this study is threefold: (1) to establish quantitative measurement and analysis methods for vitality-related street-built environment features at the micro-scale through empirical research based on DCNN technology and provide a replicable paradigm for the spatial measurement; (2) to propose a new method for micro-scale measurement by street view images combined with semantic segmentation and drone recording combined with multi-object tracking techniques; (3) to elaborate the nonlinear relationship between morphological, functional, human-scale features and street vitality using GBDT.

The remainder of this paper is organized as follows. **Section 2** illustrates the site and research methodology, and **Section 3** presents the results and discussion of the vitality measurement and correlations between vitality and the physical street environment. **Section 4** presents the conclusions as well as the limitations and further work.

2. Data and methodology

2.1 Study area and research unit

Shenzhen is a city in southern China adjacent to Hong Kong. It was the first Special Economic Zone and is now well known for high-tech and innovative industries. It is also China's youngest and largest migrant city (Tao et al., 2015). The study area, Baishizhou, was chosen as a research site due to its unique characteristics. As the largest urban village in Shenzhen, Baishizhou boasts a population of 140,000 and a community area of 0.7 km^2. Legally, Baishizhou is a part of the city, not a village, and its inhabitants are urban citizens whose land is owned by the state (Hao et al., 2013). Moreover, Baishizhou is representative of the emerging high-density informal settlement that will continue to appear in China's major cities (Hao et al., 2011). Its narrow streets, extensive public space activity, and dense pedestrian flow represent the daily life of a dense residential area in the Pearl River Delta.

We referred to the existing literature to classify streets in urban villages as the street public space, main street, street market, and lane (Song et al., 2016b). The street public space is primarily animated by irregular vendors who occasionally use the additional space of the public area to expand their business area to attract pedestrians. The main street has a high volume of pedestrian traffic and frequent daytime and nighttime activities. They are significant internal and external drivers of traffic and commercial activity. The street market is the most active area only during particular times (morning and night), which supplies food and social possibilities. Lane is the smallest unit of the urban village's internal transit system, and due to its narrow width, it forms the unique "handshake building" phenomenon.

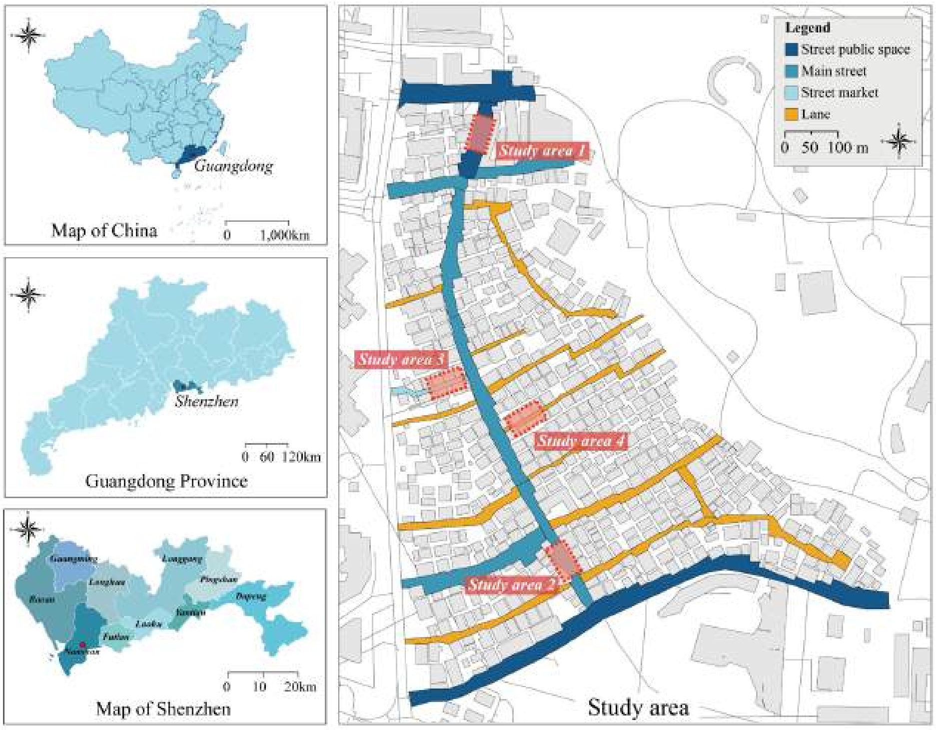


Figure 1. Study area.

As shown in **Figure 2**-a, the size of the study area is 40 by 24 meters. Considering the appropriate distance for capturing streetscape data, we divided the study area into ten primary research units (8X12m). The streetscape capture parameter of 8 m as the width is the normal visual range for a person walking in the street, which reflects the rich field of the ground floor façade of the street at the microscopic scale. Additionally, the primary research unit was used to identify dependencies analysis and nonlinear regression analysis.

Following Whyte's grid analysis method (Whyte, 1980), the primary research unit was further divided into blocks of 2m by 2m, generating a total of 240 spatial units as secondary study units to quantify the spatial and temporal distribution of street vitality. **Figure 2**-b depicts the specific locations of the study units in the four selected street types.

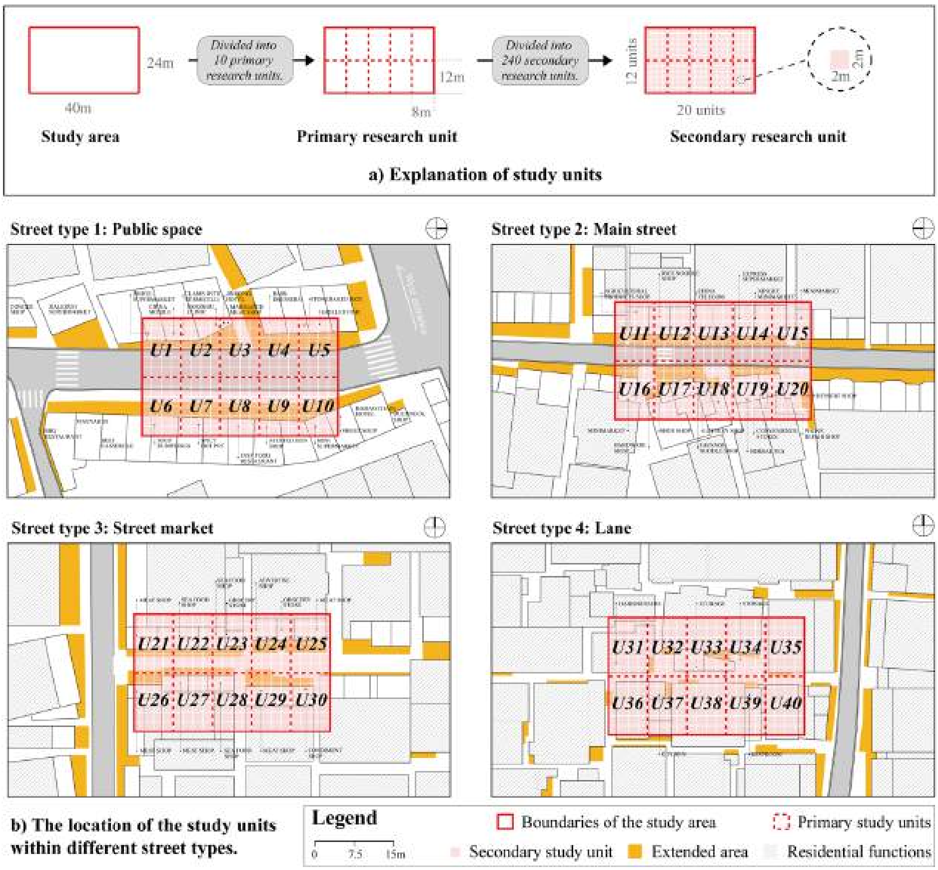


Figure 2. Explanation of the study units and their specific location in four study areas.

2.2 Theoretical framework

We developed a framework to automatically quantify the association between street vitality and street-built environment (**Figure 3**). A bustling urban street is where numerous people engage in a regular and consistent sequence of activities (Mehta, 2007). Thus, the pedestrian flow on the street can be used as a dependent variable to characterize street vitality and respond to the spatial and temporal distribution of activities. In addition, we selected the physical street environment as the independent variable. We integrated drone technology with multi-object tracking algorithms based on a DCNN to measure and analyze street vitality. Likewise, the measurement of the physical environment of the street was carried out using street view images combined with semantic segmentation, urban geographic data, and field mapping. Finally, the GBDT was introduced to capture the nonlinear regression relationship between built environment characteristics and street vitality.

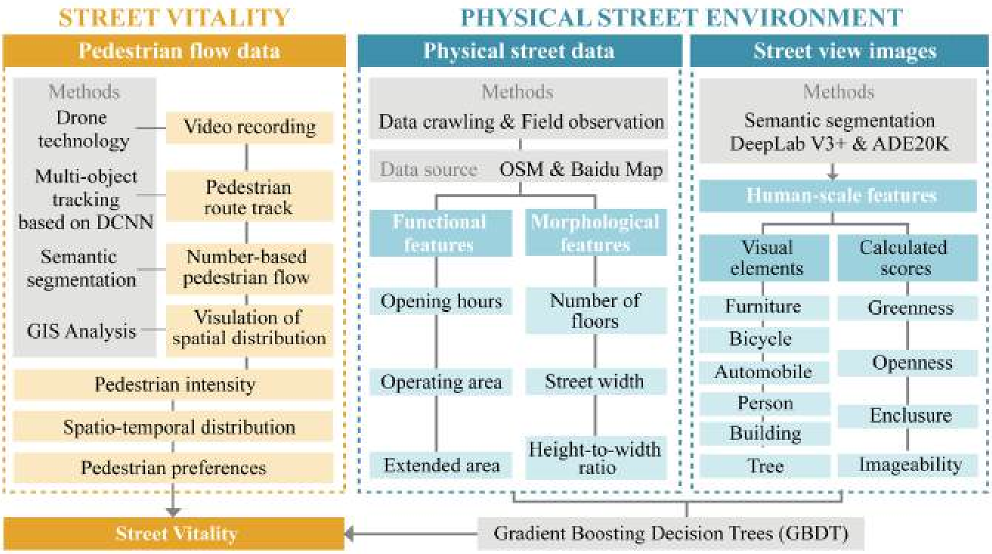


Figure 3. Analytical framework.

2.3 The selection of variables

Street vitality is the spatial expression of economic activity (Xia et al., 2020). In our work, street functional characteristics exemplifies the environmental characteristics of the street trade. Functional characteristics contain the opening hours of each shop, operating area, and extended area, which are collected by field observation. It is worth noting that the extended area is a unique micro-space in urban villages, where itinerant vendors operate from time to time and attract customers to bring life to the street. To examine the effect of street morphology and street canyons on vitality (Jiang et al., 2022), we subdivided them into three variables: number of floors, street width, and height-to-width ratio. They are downloaded from the Open Street Map (OSM) (www.openstreetmap.org) and Baidu Map (www.map.baidu.com).

Visual elements related to the street environment were extracted as explanatory variables, including furniture, person, buildings, and tree. The integrated visual elements consist of street furniture, bicycles, and automobiles. The street furniture includes a door, table, curtain, chair, shelf, armchair, seat, railing, and bench. The bicycle element results from combining the minibike and the bicycle. The automobile element is a combination of car, bus, and truck. All visual elements reflect the proportion of individual variables of the street environment features.

Four indices were defined based on recombining the parsed visual elements from streetscape images and were used to multidimensionally represent the human-scale perception scores of streets' physical environment. **Table 1** illustrates specific explanations and formulas of indices (Eq. 1-4). Greenness denotes green landscape features such as grass, trees, vegetation, and green belts. It determines pedestrians' active awareness and access to the distribution of street vegetation (Ma et al., 2021). Openness refers to the visibility of the sky and determines the brightness and access to the sky from the commuting environment (Tang and Long, 2019). Enclosure represents the degree of human scale. The percentage of vertical elements to the overall pixel is measured (Ewing and Handy, 2009; Rapoport, 2016). Imageability responds to the richness of the built environment and street furniture, with objective elements including signboard, sculpture, person, and bench (Ma et al., 2021).

Table 1

Formulas and explanations for indices.

Indices	Formula		Explanation
Greenness	$G_i = \frac{\sum_{i=1}^{4} T_i + G1_i + P1_i}{\sum_{i=1}^{4} P_i}$	(1)	T_i denotes the proportion of tree pixels, $G1_i$ denotes the proportion of grass pixels, $P1_i$ denotes the proportion of plant pixels, P_i is the total number of pixels in image *i*.
Openness	$O_i = \frac{\sum_{i=2}^{4} S_i}{\sum_{i=1}^{4} P_i}$	(2)	S_i denotes the proportion of sky pixels.
Enclosure	$E_i = \frac{\sum_{i=1}^{4}(B_i + T_i + W_i + F_i)}{\sum_{i=1}^{4}(100 - S_i)}$	(3)	B_i denotes the proportion of building pixels, W_i denotes the proportion of wall pixels, F_i denotes the proportion of fence pixels.
Imageability	$C_i = \frac{1}{2}\sum_{i=1}^{4}\left(\begin{matrix} C_i + P2_i + F1_i \\ +S2_i + P3_i + T_i \end{matrix}\right)$	(4)	C_i denotes the proportion of cabinet pixels, $P2_i$ denotes the proportion of person pixels, $F1_i$ denotes the proportion of furniture pixels, $S2_i$ denotes the proportion of signboard pixels.

2.4 Data collection

We chose the DJI Mavic 2s (https://www.dji.com/ca/air-2s/specs) for measuring street vitality (**Figure 4**). DJI Mavic 2s is a device to provide aerial imagery for recreational and professional use. It has an integrated three-axis gimbal-stabilized camera with a specially engineered wide-angle lens. This enables the capture of highly detailed 20-megapixel photos and stable 4K videos in various lighting conditions. We experimented with flight heights of 15m, 25m, 35m, and 60m and finally settled on 25m as a fixed parameter. 25m with the UAV camera lens can capture a 40m by 24m top view of the street within site, which helps to measure the street space at a microscopic scale.

We chose sunny days with average temperatures ranging from 22° to 28° to conduct the site experiments. Data sampling was conducted throughout the day from 6:00 am to 6:00 pm. Each interval of data collection was 2 hours. The procedure consisted of equipment inspection, flying the drone while recording, uploading the video to a laptop, and replacing the battery pack before the next recording. Consequently, each street type has seven 10-minute aerial videos, for a total of 280 minutes as a sample.

Regarding street view images, we used the Nikon D810 and lenses from Nikkor 28-300 mm to collect data. The street view image acquisition is based on the secondary study unit, with photographs taken every 8 meters on both sides of the street at fixed times and points to reflect the street scene. Street view image acquisition was made in parallel with drone recording. The images were captured at angles of 0°, 90°, 180°, and 270° to display the entire surroundings, while the camera was positioned at 1,6 m, the angle was 120°, and the pitch angle was 0°. We collected 560 images of streetscape images from different time eras.

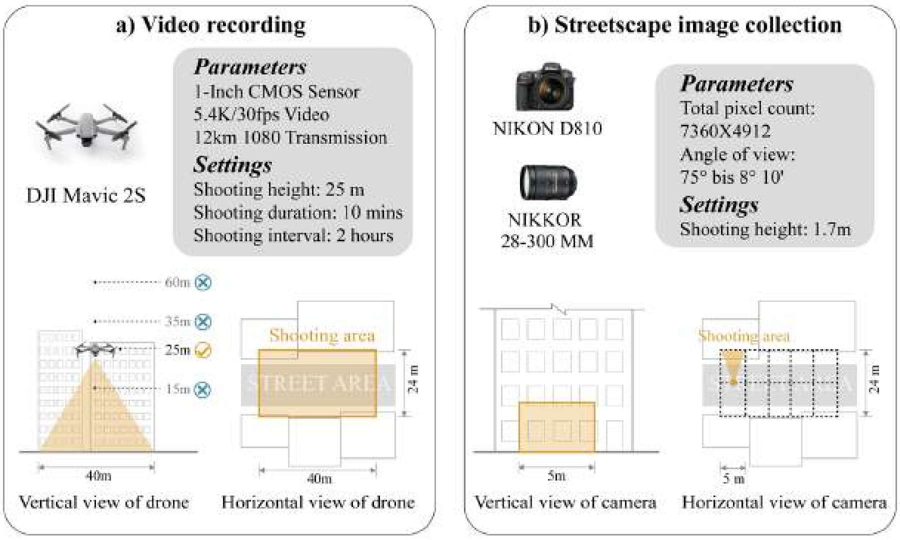


Figure 4. Information of sampling devices and shooting protocol.

Notes: **Figure 4**-a) shows the DJI Mavic 2S, a shooting tool for collecting pedestrian flow, and the parameters of the drone; **Figure 4**-b) shows the tool for streetscape image acquisition for identifying the street environment and the parameters of the camera.

2.5 Multi-target tracking and semantic segmentation based on DCNN

Multi-target tracking is a significant domain in DCNN and computer science. To recognize multi-objects in the video, we used a high-speed detection tool - YOLO V7 (Wang et al., 2022) and deep feature extraction based on convolutional neural networks. YOLO is a deep learning target detection technology based on the regression method that integrates target area prediction and targets category prediction into a single neural network model (Tan et al., 2018). Compared with traditional target detection algorithms, YOLO uses only one network to calculate and predict, so YOLO is much faster.

We selected the MS COCO pre-training dataset (Liu et al., 2020), which contains 91 target classes and is capable of conducting coherent recognition in context.

The step-by-step sequence for our framework is shown in **Figure 5**-a and **Figure 5**-b. The input video is pre-segmented sequentially to form 16,800 frames and then sent to the YOLO detector. YOLO extracts all potential target object features in each frame at the beginning of object tracking, assigns individual IDs to different objects, and stores position vectors. For the following images, the current object ID is attempted to be carried forward. The ID is deleted if the object is out of the image range. New objects appearing will be given new IDs. Next, RGB channels are assigned to the trajectories of each ID and then flattened and stored. Finally, by extracting the pixel-level RGB information from DeepLab V3+, the density of the trajectories in the secondary study unit is calculated, and the pedestrian flow is quantified.

DeepLab V3+ is a state-of-art deep learning model for semantic image segmentation, where the goal is to assign semantic labels. Based on DCNN, the DeepLabv3+ model has an encoding phase that extracts the essential information and a decoding phase that reconstructs the output of appropriate dimensions. We use ADE20K as our pre-trained model to identify different street elements for further calculation. ADE20K contains 150 targets. We selected greenery, sky, buildings, roads, street furniture, to calculate the physical environment of the street on a microscopic scale (Ewing et al., 2016; Nagata et al., 2020).

As illustrated in **Figure 5**-c, we utilize cameras to acquire streetscape images in three directions of the primary research units. The acquisition of streetscape images in each unit can reflect the richness of the street façade, the state of street stores, the street canyons, and the complex street traffic environment. DeepLab V3+, in conjunction with ADE20K, was used to determine the percentage of various street visual elements for quantitative examination of human-scale streetscape features.

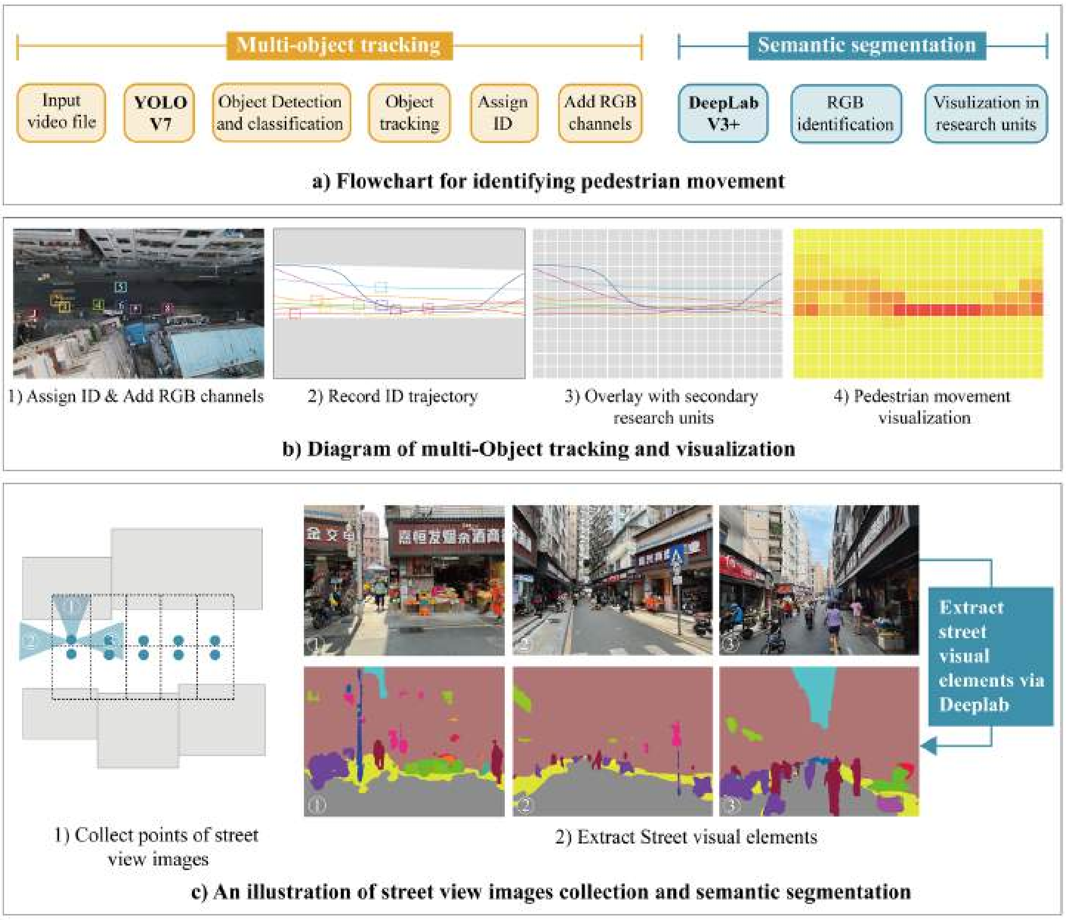


Figure 5. An illustration of multi-object tracking and semantic segmentation.

2.6 Nonlinear regression modeling based on GBDT

This study employs gradient boosting decision trees to examine the relationships between the physical street environment and street vitality. The content of this subsection is mainly derived from Yang et al. (Yang et al., 2021). The GBDT model predicted and accounted for nonlinear relationships between variables and was first applied in computer science (Friedman, 2001).

Based on statistical and machine learning methods, the GBDT approach combines decision trees and gradient boosting. It first groups samples through decision trees. The observed mean in each group is then used to predict the observed values. The errors generated in this process help to correct the weight of the independent variables for the next classification. GBDT will calculate the prediction error at each stage of the iteration and select the number of trees that minimizes the prediction error. The model with the optimal number of trees is the basis for further analyses. Gradient boosting aggregates many simple models into one complex model in a sequential procedure (Elith et al., 2008). The mathematical notation of the GBDT algorithm is as follows.

Assuming that × is a set of explanatory variables (i.e., built environment attributes in this study) and $f(x)$ is an approximation function of the response variable y (i.e., BHI), the GBDT method estimates the function as an additive expansion of basis function h $(x;\ a_m)$ (Chung, 2013; Saha et al., 2015):

$$f(x) = \sum_{m=1}^{M} f_m(x) = \sum_{m=1}^{M} \beta_m h(x; a_m)$$

where a_m is the mean of split locations and the terminal node for each splitting variable in an individual decision tree h (x; a_m), βm is estimated by minimizing a specified loss function $L(y, f(x)) = (y - f(x))^2$. Further estimation of parameters and the summary of its algorithm are elaborated in the supplementary material. The GBDT has the following advantages: (1) it does not preformulate linear or nonlinear between variables and explains the proper relationships between variables better than traditional regression models (Yang et al., 2021); (2) it can accommodate missing values and outliers; (3) it does not produce p-values and cannot test whether the observed effect of independent variables is due to sampling error, thus reducing false assumptions and significant p-values; (4) it can demonstrate the relative importance of independent variables and the interrelationship of bivariate variables.

We use the GBDT model to produce a partial dependence plot to illustrate the relationship between an independent variable. Another highlight of our study is using GBDT to analyze the relationships between bivariate variables.

3. Results and discussion

3.1 Quantitative results of the spatial and temporal distribution of street vitality

In the object detection process, the location and activity trajectory of each object in videos were obtained using a DCNN. Four datasets containing information on people in each street were generated using the method we introduced before. **Figure 6** illustrates the pedestrian trajectories for four study areas at different times. The different RGB colors represent the various target items.

The first study area documents the utilization of the street public space. Based on the basic principle of walking on the right in China and the exit location shown in **Figure 2**, most pedestrians leave the urban village between 6:00 and 8:00 a.m. (**Figure 6**-1-a); similarly, the number of pedestrians returning to the urban village increases between 4:00 and 6:00 p.m. (**Figure 6**-1-c). The morning and evening peaks affect pedestrians in the urban village, as can be observed. Other hours exhibit staggered and intertwined pedestrian trajectories (**Figure 6**-1-b), indicating that some pedestrians are attracted to street businesses.

The second study area recorded the use of the main street. Unlike the first study area, the morning and evening peaks had no significant influence here. There were no notable differences in pedestrian movement on the main street based on the time of day. Especially pedestrians walk on the roadway instead of the sidewalk here. Possibly because the narrow street does not provide sufficient space for cars and pedestrians, causing bicycles and automobiles to occupy the sidewalk (**Figure 6**-2a).

The third study area records the pedestrian activity on the street market. In contrast to the street public space and the main street, where only a small amount of pedestrian flow is present in front of specific stores (**Figure 6**-3-a), the street market is considerably less active. Due to its function, we anticipated that the street market during early morning hours would attract a relatively large number of pedestrians; however, the findings did not support our hypothesis.

The fourth study area documents the pedestrian activity on the lane. There is only a little pedestrian commuting along the lane. However, there is a considerable quantity of pedestrians in the pocket areas (**Figure 6**-4-a). This shows that pedestrians prefer the comparatively spacious pocket area in a restricted street environment. Pedestrians can maintain a certain distance from one another while stretching their bodies and socializing.

Figure 7 depicts the pedestrian densities generated by semantic segmentation in the secondary study unit to identify the street vitality further. Except for supporting findings from **Figure 6**, **Figure 7** further compares the pedestrian flows of different street types in parallel from a macro perspective: the effect of different street widths and types on pedestrian density is decisive. Moreover, we found that pedestrians do not commute in urban village streets according to ground sign norms. Bicycles, cars, and pedestrians share the street space in all samples.

Figure 6. Map of pedestrian trajectory in different study areas.

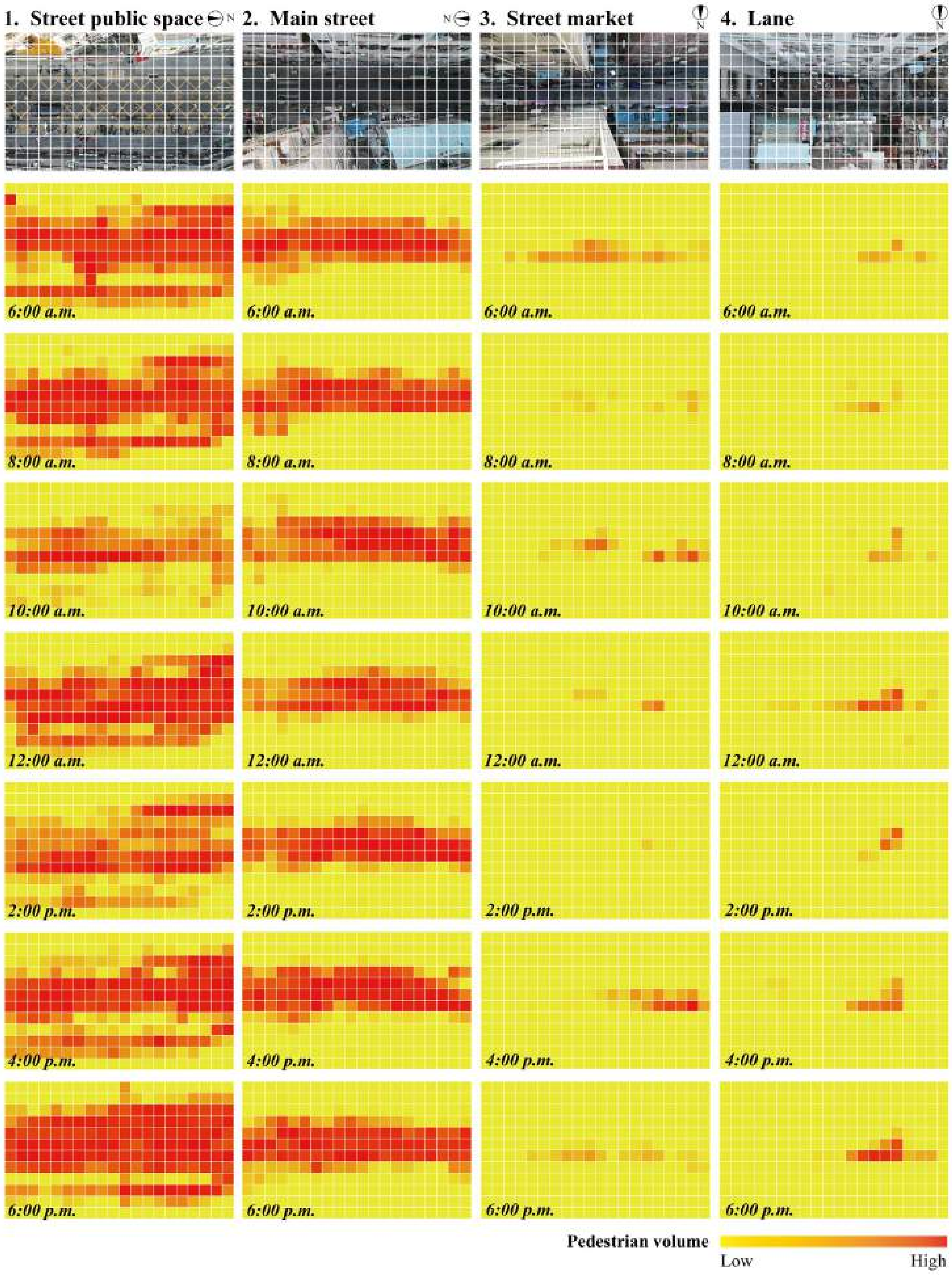


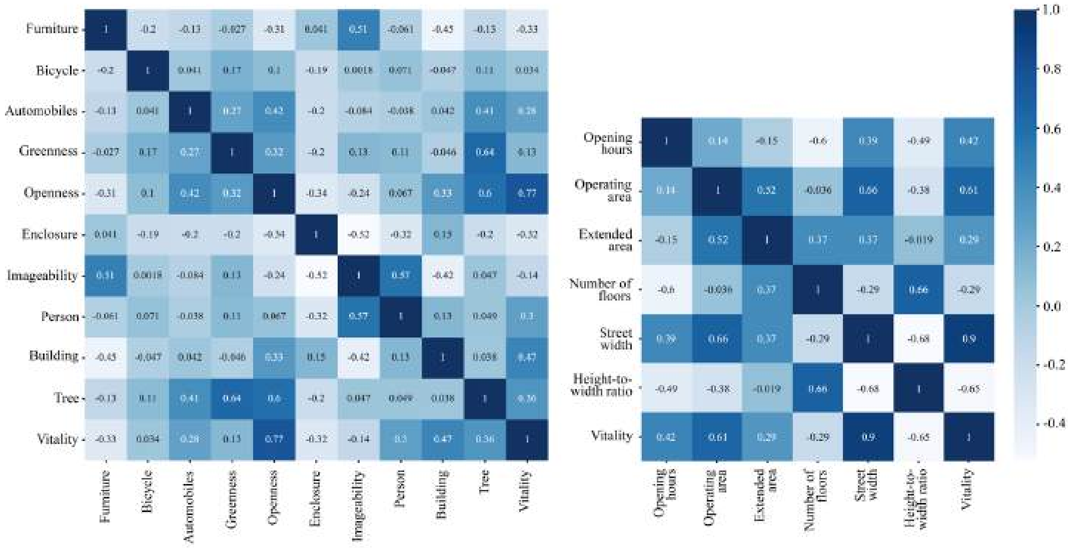
Figure 7. Heat map of pedestrian density in different study areas.

3.2 Correlation analysis and relative contribution of variables

Setting the learning rate and tree complexity parameters is particularly important in developing regression models. A greater value of learning rate, i.e., 0.1, is too fast for tree complexity and the number of trees to minimize the error (Elith et al., 2008). Therefore, we referred to the learning rate of 0.001 used by Chung (2013) and Guelman (2012), which has lower predictive deviance and reasonable tree size. Tree complexity can reflect the true interaction among the explanatory variables (Hastie et al., 2009). We tested a series of models by sequentially increasing the interaction depth level of trees from one to ten to acquire reliable tree complexity. Due to the variance in sample sizes, the dataset is split into two subsets, i.e., a subset of street human-scale features and a subset of street functional and morphological features. 20% of each subset is inputted as the testing data, while the remaining subsets (80%) are used to train the model (Ding et al., 2018). The coefficient of determination (R^2) measures the degree of correlation between the observed and predicted values. The R^2 of the first model is approximately 0.994 for the train set and 0.723 for the test set, while the second model is approximately 0.964 for the train set and 0.789 for the train set.

Figure 8 depicts the correlations of various variables in both models. **Figure 8**-a demonstrates that street furniture positively correlates with imageability (0.51). Bicycle lacks a significant relationship with the other variables (less than 0.2). Next, automobile has a weak positive correlation with openness and trees at 0.42, implying that open streets may provide more room for car commuting and street trees. Greenness and trees have a high positive correlation of 0.64. The critical finding here is that openness and vitality have a high positive association of 0.77, whereas enclosure has a moderate negative correlation of -0.32 with vitality. Wider streets and open spaces are needed to bring more pedestrian vitality to urban villages. In addition, buildings and trees have a low positive correlation with a vitality of 0.47 and 0.36, respectively, indicating that an adequate quantity of buildings and vegetation will boost street vitality.

Figure 8-b illustrates the correlation between street functional and morphological variables. We found that opening hours of street shops, operating areas, and extended areas positively correlate with street width and vitality. The analysis of street morphological characteristics is similarly consistent in that street width has a significant positive association with vitality, reaching 0.90. In contrast, the number of floors and the height-to-width ratio of the street has a weak and moderate link with vitality, respectively. Given the street width, the ratio of narrow street canyons has a significant negative effect on pedestrian traffic.



(a) correlation between human-scale street features and street vitality.

(b) correlation between functional and morphological features and street vitality.

Figure 8. Correlation analysis of variables in two models.

Table 2 shows that openness and street width contribute 37.9% and 50.3% to the relative contribution in the two models. It reveals a vital role for the width of the streets, in line with the findings in **Section 3.1** and the existing arguments demonstrating the positive effect of street width on vitality (Ewing et al., 2016; Li et al., 2022).

Regarding human-scale street characteristics, architectural elements occupy the second most important position, contributing 10.6%. Next, imageability (9.9%), bicycle (9.9%), and person (9.8%) occupy the third, fourth, and fifth positions, respectively. The diversity and richness of street components affect the vitality value. Surprisingly, trees and greenness are in last place. This differs from earlier research findings (Li et al., 2022; Wu et al., 2023). This is due to the peculiarity of the sample, i.e., the absence of greenery in the urban villages may have led to the disparity in observed results.

In terms of street functional and morphological features, the morphological characteristics constitute a total contribution of 75.3%, while the functional aspects make up 24.6%. Specifically, street height-to-width ratio and opening hours contribute 23.9% and 12.4%. Interestingly, the contribution of the extended area is twice that of the operating area, implying that having more extended area in urban village streets is highly expected for business. These findings have policy implications as they can help guide the street redesign process.

Table 2

Relative contributions of independent variables on street vitality.

Categories	**Variable**	**Rank**	**Relative importance**

			(%)
Street human-scale features	Furniture	6	0.072
	Bicycle	4	0.099
	Automobile	8	0.052
	Greenness	10	0.013
	Openness	1	0.379
	Enclosure	7	0.066
	Imageability	3	0.099
	Person	5	0.098
	Building	2	0.106
	Tree	9	0.026
Street functional and morphological features	Opening hours	3	0.124
	Operating area	5	0.042
	Extended area	4	0.080
	Number of floors	6	0.011
	Street width	1	0.503
	Hight-to-width ratio	2	0.239

3.3 Partial dependence of independent variables on street vitality

To further explore how built environment variables affect street vitality, we use partial dependence plots to illustrate these associations. After considering the average joint effects of all variables in the model, the partial dependence plot shows the dependence between the response variable and a set of features (Saha et al., 2015). Compared to traditional models, which assume a linear relationship between the explanatory variable and the response variable, GBDT does not assume a relationship. This difference is essential for understanding the impact of changes in individual variables.

Figure 9 illustrates the partial dependence (PD) of different human-scale streetscape features on street vitality. **Figure 9**-a depicts an increasing trend in street vibrancy up to 4% of the visual proportion. The effect remains stable beyond 4%. A similar trend was also found regarding imageability (**Figure 9**-j). The street vitality increases with imageability when the value of imageability is less than 8 and stays constant above 8. Within the limited width of an urban village street, a moderate amount of street furniture offered by street shops can enhance commercial services and boost imageability and vitality. According to **Figure 9**-b and c, bicycles have a slightly negative connection with vitality, whereas automobiles have minimal influence on vitality. Thus, renovating streets in urban villages may not require traffic calming measures or access restriction measures. From **Figure 9**-d, pedestrians as visual elements do not exhibit a clear trend with street dynamics. These finding questions the theory of "people attract people on street" by Gehl (Gehl, 1987; Gehl et al., 2006). The reason is that the mutual attraction of individuals on the street presupposes the involvement of stationary activities. In contrast, active pedestrian activity predominates the study area. Furthermore, openness has a substantial positive link with street vitality, while enclosure has a negative relationship (**Figure 9**-h, -i). This supports the conclusion drawn in **Table 2** that the wider streets in urban villages attract more pedestrian flow. According to **Figure 9**-e, there is no significant change in street vitality values when buildings account for less than 55% of the total visual proportion; vitality rises with increasing building proportion between 55%-65%; and drops consistently when above 65%. This suggests that appropriate building spacing and proportion of building elements, i.e., 55%-65%, supports pedestrian activity, while excessively dense building clusters or open urban environments are less inviting to walkers. Compared to previous studies (Yin and Wang, 2016), our findings establish empirical evidence for the current urban form and the relationship between street canyons and vitality. Lastly, **Figure 9**-f and g indicate a negative trend between vitality, greenness and tree, implying that greenness may not be the primary consideration for street renovation in urban villages.

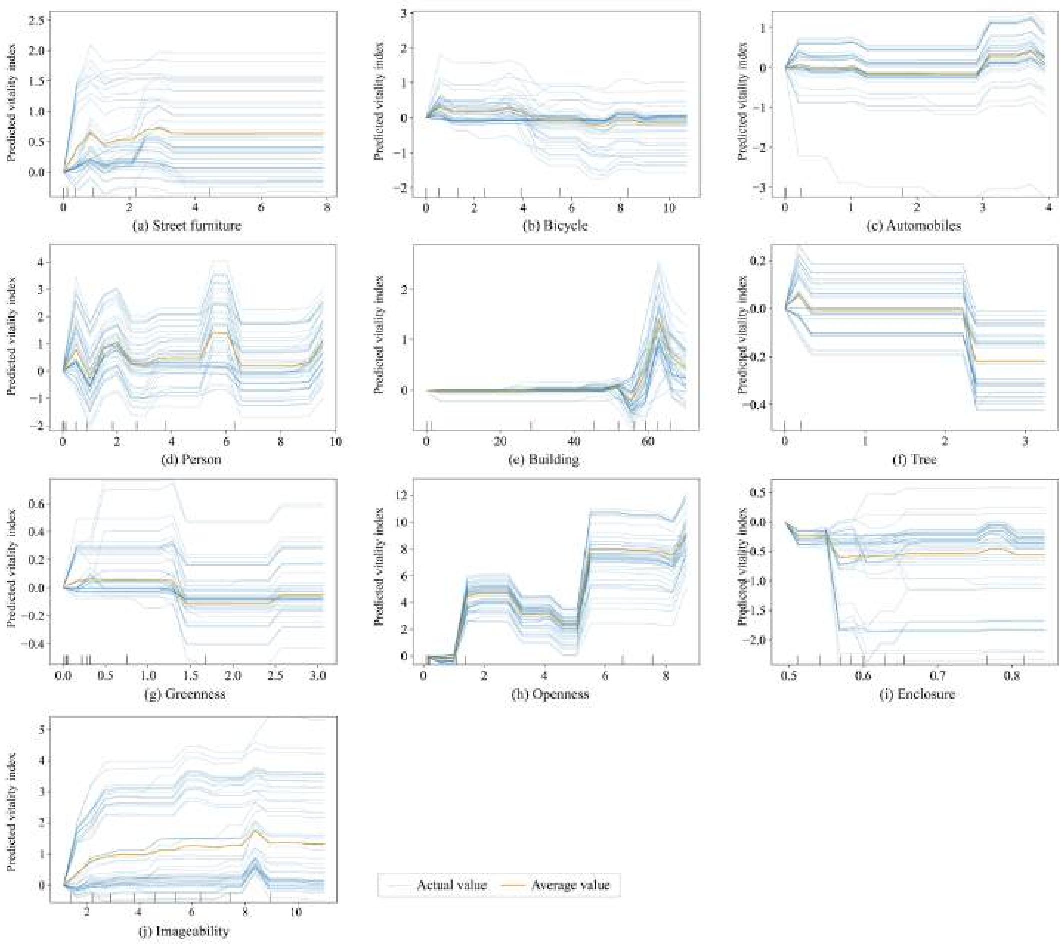


Figure 9. Partial dependence of street human-scale features on street vitality, with GBDT.

As shown in Figure 8, we continue to employ partial dependence plots to illustrate the impact of street functional and morphological characteristics on street vitality. We found that the opening hours have a negative effect on vitality (**Figure 10**-a). The larger the operating area of the shops, the more pedestrian traffic they attract (**Figure 10**-b). However, the non-linear relationship demonstrates that the street dynamics stay stable when the operating area reaches 23 to 55 square meters. Meanwhile, the extended area of shops is in the range of 0-2 square meters, and vitality decreases, but when it is more than 2 square meters, street vitality increases steadily. When the expansion area is limited, stores may prefer indoor operation space. Nevertheless, when additional outdoor expansion area is adequate, stores can achieve positive results slightly (**Figure 10**-c).

As for street morphology, in addition to the findings on street width, floor levels also have a beneficial effect on street vitality (**Figure 10**-d). The height-to-width ratio of the street canyon demonstrates a negative, nonlinear relation with vitality (**Figure 10**-e). When the value is around 1, the highest street vitality is presented. However, when it is more significant than 1.8 when the high residential buildings are equipped with extremely narrow streets, the vitality shows a clear decreasing trend, consistent with the observations in **Figure 6** and **Figure 7** (lanes).

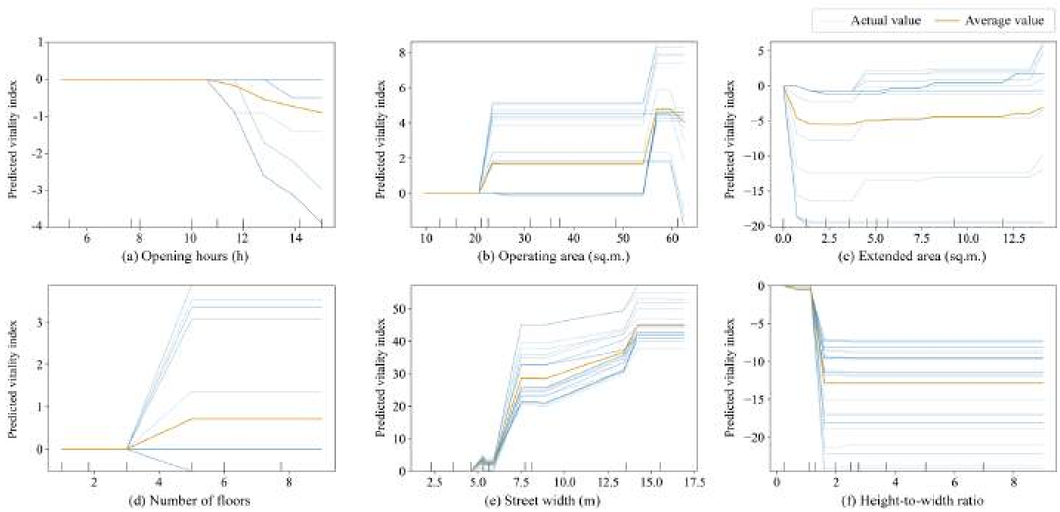


Figure 10. Partial dependence of street functional and morphological features on street vitality, with GBDT.

3.4 Test of bivariate contribution to street vitality

Figure 11 illustrates the bivariate contribution of human-scale street features to street vitality in three dimensions, where the ranking references the importance of the variables in **Table 2**. According to **Figure 11**-a, openness accounts for 37.9% of the importance; it dominates the bivariate results; thus, we display the other four variables (building, imageability, bicycle, and person) in combination with openness. Overall, street vitality tends to increase, except for a slight decline when openness is between 3 and 5. It provides evidence that street openness contributes to pedestrian activity, street commerce, and street safety performance in urban villages (Wu et al., 2023; Yin and Wang, 2016). It is worth mentioning that only the lower imageability has a negative effect when openness is high. In other words, a wide urban street with sufficient street components, e.g., street furniture, trash bins, and signboard, is sufficient to draw crowds. As shown in **Figure 11**-b, the bivariate results of building and other variables vary. When the proportion of the building is higher than 55%, all variables have no effect on vitality except for the person, which has a decreasing and then increasing effect on vitality. When building proportion is lower than 55%, imageability, furniture, and automobile positively impact vitality, whereas bicycles and enclosure negatively impact it. This implies that street elements and even traffic contribute to pedestrian commuting when building density is reasonable (under 55%), while adding bicycles may reduce street vitality due to safety reasons (Ewing and Dumbaugh, 2009). In **Figure 11**-c, the effects of bicycles, furniture, automobile, and greenness on street vitality are weak when imageability is held constant, but the person has a more significant effect. When the street imageability remains unchanged, the influence of pedestrians on vitality is more random but in a facilitating role due to the non-linear rising trend. In **Figure 11**-d, bicycles and furniture are positively supportive of vitality. However, the bivariate effect of bicycles, enclosure, and greenness on vitality is negative. The conclusion is consistent with **Figure 11**-b. In addition, the data results presented in **Figure 11**-e, f, g, and h further support the findings above.

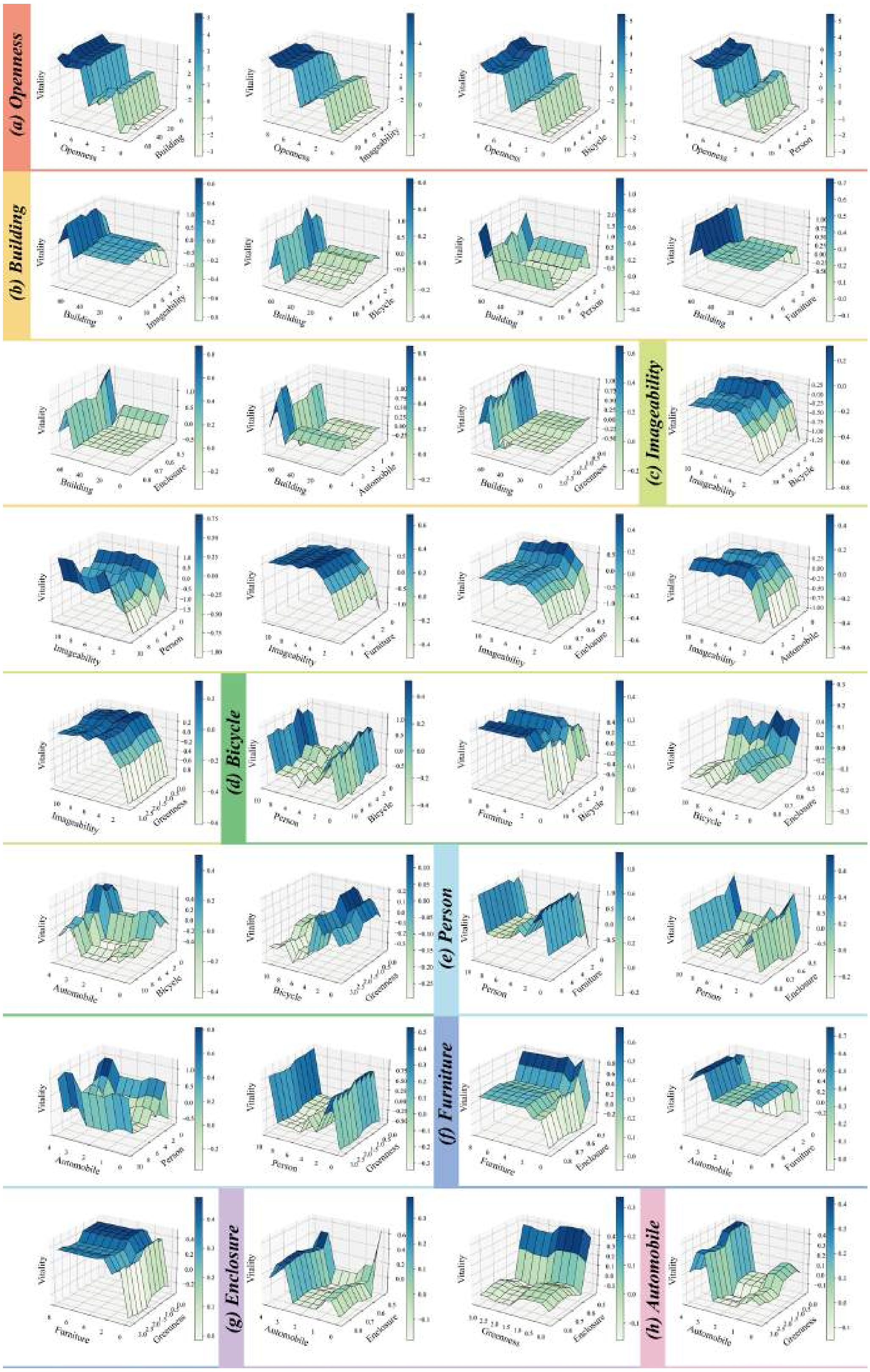


Figure 11. Analysis of bivariate contribution of human-scale street features to street vitality.

4. Conclusion

In short, we adopt a quantitative approach to explore the micro-level association between street vitality and built environment characteristics in high-density residential areas to provide more comprehensive insights into the formation of vitality.

At the theoretical level, this study examines the changes in the physical environment of streets and the vitality of various street forms in urban villages at different times of the day. First, this empirical study addresses a gap in the literature on street vitality in urban villages specifically related to the micro-physical environment. We demonstrate the high inclusivity of urban village streets and the spatial heterogeneity of vitality in different periods. It also provides innovative ideas from the perspective of residents' daily activities. Second, to prevent the influence of a single environmental variable on street vitality, we evaluated the factors affecting street vitality in terms of morphology, function, and human scale. Third, this study emphasizes the potential benefits of integrating multiple street elements for micro-renovations in urban villages, which offers valuable insights for the transformation of urban village streets as part of the "Shenzhen Urban Village Comprehensive Improvement Master Plan (2019-2025)" and "the new urbanization implementation plan during the 14th Five-Year Plan period (2021-2025)."

At the technical level, this study is a further attempt to automatically map the usage of small public spaces following Hou et al. (2020). Using the drone in place of traditional devices, we avoided the complex algorithms and potential errors resulting from the different perspective angles in earlier studies. Meanwhile, drone technology can precisely capture complex trajectories of moving objects over relatively broad areas. The method can be a state-of-the-art reference for various active traffic planning practices and studies. Second, we propose to employ grid segmentation to transform the pedestrian into the projection coordinates of the real world. The RGB channels generated by the activity trajectories were used with semantic segmentation to calculate pedestrian density in the grid. The cumulative trajectory of each grid can reflect micro space usage. Third, we conducted two-and three-dimensional partial dependence analyses of variables affecting street vitality by GBDT. Compared to the simple linear relationships, we present nonlinear findings that assist in identifying synergistic effects and conflicts between single and bivariate variables and street vitality. This provides microscopic quantitative guidance on improving overall street vitality in high-density residential areas and the latest urban village street regeneration challenges.

In addition to these contributions, this study has the following limitations. We did not analyze the study area after 6 p.m. due to the technical limits of the drone operating environment and multiple target identification. Nevertheless, the vitality of night markets in urban villages and mobile retail are equally valuable to study. Spatial vitality analysis and pedestrian studies for nighttime may need to be supplemented with additional techniques. Furthermore, we have only examined representative streets in urban villages. Using our methodology, further studies could be conducted on more urban public spaces, such as campus squares, commercial areas, and train stations.

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Chapter 6

Results and discussion

6.1 Internal connections and co-findings in publications

In this chapter, I explored how four interconnected publications respond to and reflect four central research questions. These papers not only share intrinsic connections but also jointly unveil the complex interplay between street design, resident behavior, and mental well-being. Herein, I detailed how these publications integrate and expand our understanding of comprehensive streetscape assessment, adaptability in UVs, residents' perceptions and mental health, and the impacts of daily mobility.

Papers I and II focus on quantifying walkability and mobility of streets and enhancing the comprehensive assessment of street design from a human-centric perspective. These papers propose a more holistic assessment framework by integrating indicators of walking potential and walkability, aiming to understand and improve the livability and social functionality of street spaces. Emphasizing the integration of subjective perceptions and objective data in street planning, the research addresses the question of how to construct a comprehensive system for assessing street environments.

The investigation extends into the specific context of UVs, exploring how to adapt German quantitative methods to these informal residential areas. Through field research and technological applications, such as drone monitoring and social media data analysis, Papers II, III, and IV introduce an innovative method for measuring and enhancing the streetscape of UVs. This approach not only deepens the understanding of physical and perceptual qualities of streets but also fosters the development of more inclusive and humane urban spaces.

Paper III utilizes data from social media platforms to analyze residents' perceptions of and reactions to the UV environment. By examining residents' positive sentiments and the overarching residential environment, this paper reveals how street design influences residents' mental health and the livability of neighborhoods. This resident feedback-based approach provides a vital human-centric perspective for street planning and design, closely relating to the research question of how environmental improvements can enhance residents' positive sentiments and livability.

Lastly, Paper IV employs quantitative methods to analyze the daily mobility behaviors of UV residents, examining how enhancements to micro-scale streetscapes can bolster overall urban mobility. This research underscores the importance of understanding and assessing street usage patterns in optimizing urban mobility and improving residents' quality of life. The in-depth analysis of daily mobility addresses the research question of how to supplement the understanding of macro urban mobility.

6.1.1 The role of quantification of mobility and human-oriented perspectives in the street assessment framework (Co-findings from Paper I & Paper II)

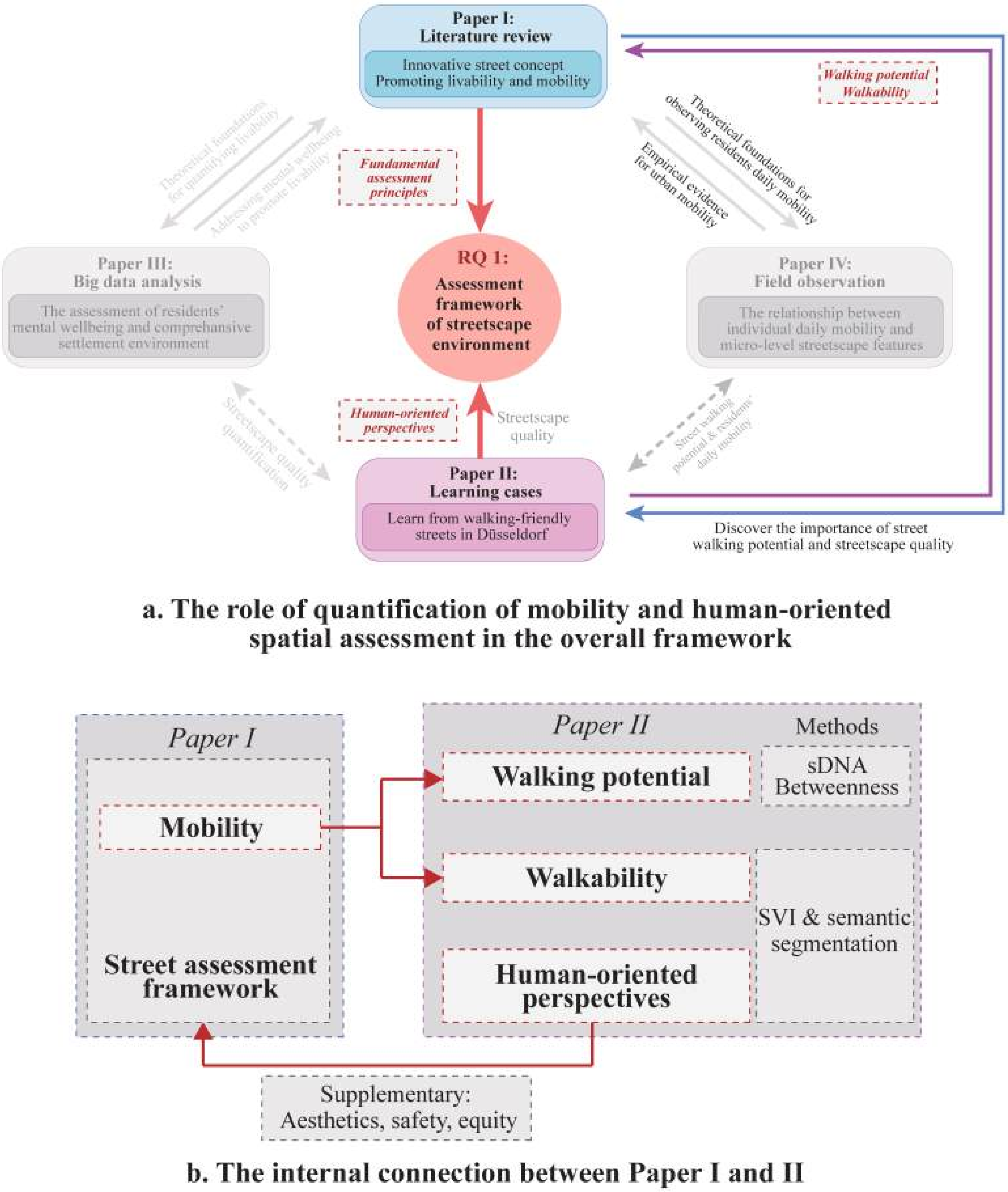

Figure 6.1: (a) The role of quantification of mobility and human-oriented spatial assessment in the overall framework, and (b) The internal connection between Paper I and II.

Düsseldorf's research further transformed the overview's concept of "mobility" into two aspects: walking potential and walkability (Figure 6.1). On one hand, the concept of walking potential directly reflected the core goal of mobility: ensuring pedestrian convenience while enhancing the effectiveness of street facilities. Streets with high walking potential, calculated using sDNA, usually exhibited higher connectivity, allowing pedestrians to reach their destinations more efficiently, achieve greater freedom of movement, and meet various travel needs. On the other hand, compared to recent studies (Miller et al., 2022), this focus on walking potential highlighted the direct impact of connectivity on walking decisions, whereas Miller emphasized the influence of socio-economic factors on walking potential. Walkability, more intuitively, reflected the degree to which streets were pedestrian-friendly and convenient. In Düsseldorf's study, walkability was assessed by calculating the proportion of walkways in relation to the entire street. The walkability of streets correlated closely with residents' willingness to travel and behavior patterns, effectively characterizing mobility in terms of street infrastructure, which in turn influenced the interaction between street planning and pedestrian activity (Koo et al., 2022).

Unlike the direct transformation of mobility into spatial indicators, I translated livability into a human-centered perspective. This approach aimed to assess urban spaces' actual usage and environmental quality from the pedestrian's point of view. In this process, livability manifested as a focus on the pedestrian experience, including providing comfortable walking environments, rational greenery layouts, appropriate traffic segregation, and attractive streetscape designs. This human-centered perspective was an innovative research method, consistent with Liu et al. (2020b) 's study, which also emphasized evaluating urban spaces from the user experience perspective through big data analysis of usage patterns. The significance of this transformation lay in its focus on individual experiences and needs within street spaces on the basis of translating mobility into walking potential and walkability, aiding in the creation of street spaces that better aligned with residents' daily habits (Bozovic et al., 2020).

Paper II emphasized street spatial quality, further augmenting street identity and characteristics. Firstly, the quality of street spaces directly affected pedestrian experiences and behavioral choices. By focusing on metrics such as greenery, enclosure, and visibility, the livability of streets was enhanced, attracting more people to walk or use other low-emission modes of transport. Good street greening and pedestrian facilities made urban residents more comfortable and willing to stay during commuting and social activities, thereby fostering social interaction and enhancing the social function and livability of streets (Nieuwenhuijsen, 2021). Secondly, improving street visibility and enclosure significantly impacted urban mobility. Narrow and enclosed commercial districts and residential areas typically attracted more pedestrians, whereas open spaces were better suited for recreational activities. Thus, by introducing appropriate streetscape elements such as trees, signage, and street furniture, the visual appeal of streets could be improved, enhancing their functionality in terms of mobility. Additionally, incorporating landmark buildings and open street facades helped enhance street recognizability and attractiveness, increasing the diversity of social activities (Elhagla et al., 2020).

Beyond livability and mobility, focusing on street spatial quality also complemented street identity and characteristics from other aspects. Firstly, aesthetics and cultural values were important components of street identity (Hu et al., 2022). Through diversified street facade designs and skylines, streets could present a differentiated urban image, enhancing their recognizability. Secondly, enhancing the quality of street spaces was closely related to safety. High-quality street environments provided better lighting, clear road planning, and comprehensive walking facilities, thereby reducing traffic accidents and ensuring safe travel for residents. Well-maintained street facilities, clear traffic signs, and standardized street layouts effectively enhanced residents' sense of safety while traveling. According to Holy-Hasted and Burchell (2022), high-quality public space design was closely linked to reducing urban crime rates, proposing that improving the livability and aesthetics of streets could significantly enhance urban safety.

Focusing on street spatial quality also helped strengthen the spatial equity aspect of street identity. In considering street spatial quality, it was necessary to provide equal activity spaces for residents of different ages, genders, and backgrounds, ensuring the usability of accessibility facilities, and creating an inclusive, diverse public space. In such street environments, people could freely and equally engage and interact, promoting community integration and social equity, and infusing street identity with more humanistic characteristics. Overall, Düsseldorf's street experiments, focusing on the improvement of spatial quality, not only enriched the streets' aesthetic and cultural connotations but also enhanced their safety and equity, endowing streets with unique identity traits and enhancing the overall urban image.

6.1.2 Comprehensive assessment of streetscape quality and walkability of UV streets (Co-findings from Paper II, Paper III, and IV)

The Düsseldorf experiment provided a micro-scale and human-centric perspective for studying UVs by integrating walking potential and visual spatial quality of streets. This approach revealed detailed conditions and characteristics of different districts, especially at a micro-scale (Figure 6.2). Düsseldorf's findings emphasized data collection from pedestrian viewpoints rather than traditional vehicle road imaging. This method more comprehensively captures the street environment and spatial quality as experienced by pedestrians. In my research on UVs, I further inherited and innovated this method by combining drone and pedestrian-level photography. Both approaches focus on assessing street spatial quality from a pedestrian's perspective, inheriting the concept of data collection from pedestrian pathways and providing a closer approximation to the actual users' street experiences (Hassan and Elkhateeb, 2021). Additionally, both methods emphasize micro-scale insights, enabling detailed observation of street spaces from pedestrian viewpoints. The innovation of incorporating drones offers an aerial perspective that captures the macro-structure of the entire UV, compensating for the limitations of ground-level views. This can reveal the neighborhood's spatial layout and street network, allowing researchers to understand the organization of street spaces in UVs from a macro perspective. Meanwhile, data from pedestrian viewpoints accurately reflect the environment as seen by pedestrians on the streets, crucial in the narrow and densely populated streets of UVs where close observation methods are necessary (Cui et al., 2023). Combining the macro perspective of drones with the micro insights from pedestrian paths enables a multi-layered assessment of spatial quality, linking local experiences with the overall environment to provide a comprehensive analysis of street quality and walking potential (Ma et al., 2021; Cambra and Moura, 2020).

In the Düsseldorf study, spatial quality was assessed objectively. However, spatial quality is closely linked to mental health (Sun et al., 2023; Mouratidis, 2021; Chen et al., 2021). Therefore, Paper III and Paper IV employed different methods to address the limitations of objective assessments: Paper III utilized data from the social media platform Sina Weibo to more comprehensively reflect people's subjective sentiments in UVs. By applying NLP technologies, we extracted emotional features from Weibo posts to analyze the relationship between the sentiment of UV residents and their street environments. Filtering posts by location and keywords, the study gathered a significant number of posts on themes like neighborhoods, further employing a pre-trained NLP model for sentiment analysis (Garcia and Berton, 2021). Unlike traditional objective assessments, this method mined individual subjective experiences from social media data, providing a richer, more authentic assessment of urban space quality. The shift from objective to subjective assessments better reflects the actual feelings and experiences of residents in UVs. Subjective assessments capture residents' real reactions to their environment, revealing their mental states in different spaces. Additionally, subjective data can identify links between urban spaces and residents' sentiments, reflecting diverse perspectives across different groups. Thus, subjective data can

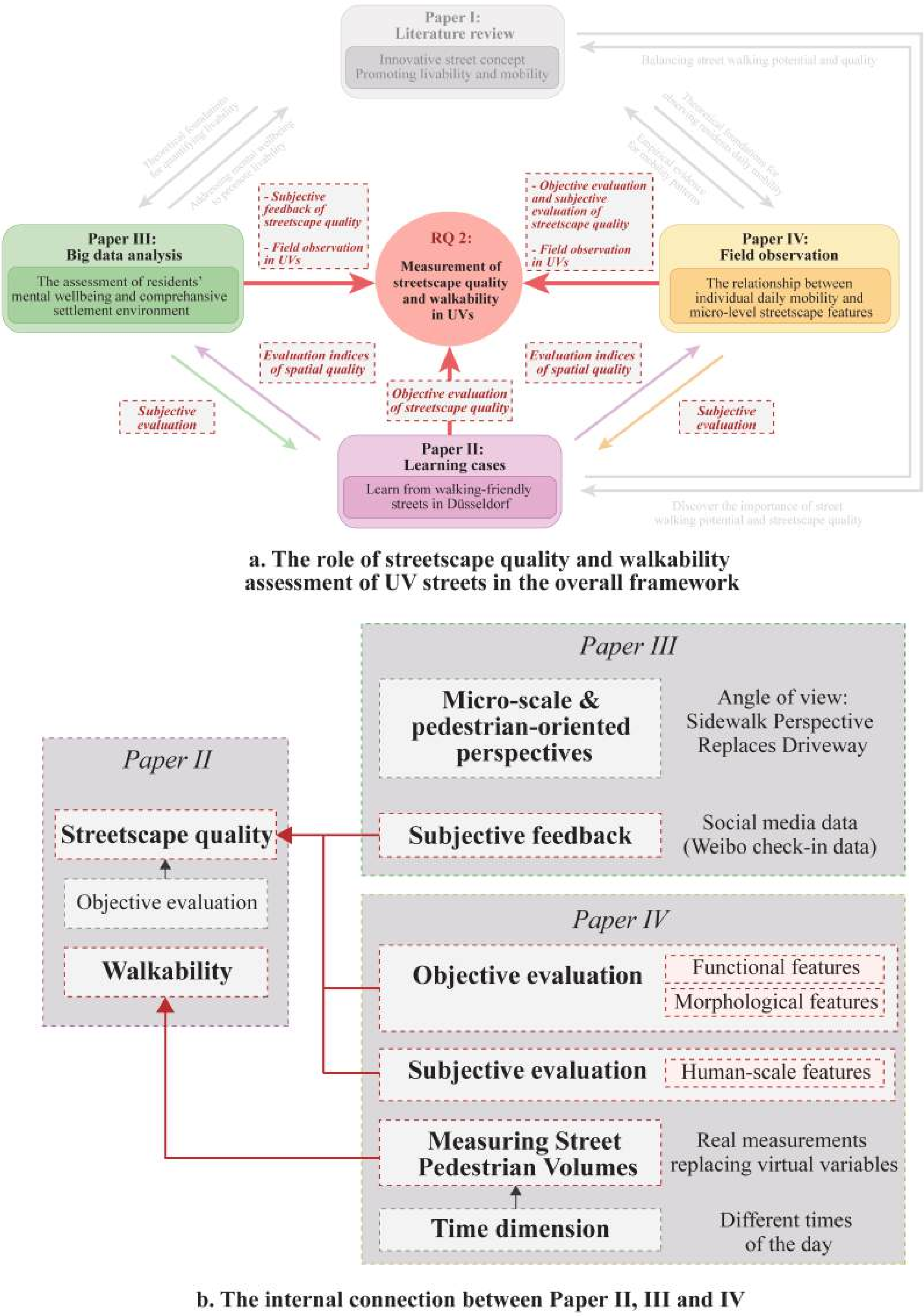

Figure 6.2: (a) The role of streetscape quality and walkability assessment of UV in the overall framework, and (b) The connection between Paper II, III, and IV.

address the shortcomings of objective assessments, offering a more detailed and comprehensive reflection of people's real needs and providing human-centered guidance for UV street planning (Cao et al., 2020).

In Paper IV, I combined objective and subjective assessment methods. Objective measurements included quantifying street functional and morphological characteristics, while subjective aspects involved quantifying human-scale street spatial quality. First, the quantification of functional and morphological features was facilitated by field inspections and online map data. Street functional characteristics, including shop operating hours, business area, and expansion zones—especially expansion zones as a unique UV space accommodating mobile vendors and attracting customers—contributed to street foot traffic. Morphological features were measured by indicators such as the number of building floors, width, and aspect ratio, with data extracted from OSM and Baidu Maps, further combined with field measurements for accuracy. Human-scale street characteristics relevant to subjective measurements were quantified through the analysis of SVIs. We categorized street visual elements into four dimensions: greenery, openness, enclosure, and recognizability. Greenery was measured by the pixel ratio of green elements like lawns, trees, and plants, affecting pedestrians' perceptions of street vegetation distribution; openness reflected the visibility of the sky, thereby illustrating street brightness and sky accessibility; enclosure was assessed by calculating the pixel ratio of vertical elements such as buildings, walls, and fences to evaluate street enclosure at a human scale; recognizability measured the richness of the street environment and street furniture, with elements like signs, sculptures, and seating reflecting street environmental recognizability and complexity. This combined method of quantifying spatial quality objectively and subjectively has notable advantages. It integrates multi-layered characteristics of streets in terms of form, function, and human scale, comprehensively reflecting the actual conditions of street environments (Yıldırım et al., 2023). By combining data sources such as drone aerial photography and SVIs, the quantified results are more representative.

Paper II discussed walkability as an objective spatial indicator within a mobility framework, whereas in the field research conducted in UVs, I translated the street walkability into a tangible measure through pedestrian flow. Utilizing DJI Mavic 2S drones and Nikon D810 cameras, the survey of UV streets was able to capture panoramic aerial imagery and streetscape photos from fixed heights and angles, thereby accurately recording pedestrian activities and environmental elements. The drone, flying at a preset height of 25 meters, provided a broad street perspective from above, offering detailed data for micro-scale analysis of the streets. The camera, through multi-angle shooting, detailed the shops and environments on both sides of the streets. Employing deep learning models like YOLO V7 and DeepLab V3+, this study achieved multi-object tracking and semantic segmentation, accurately identifying pedestrian and vehicle trajectories as well as the composition and distribution of street elements. The results showed that different types of streets exhibited unique patterns of pedestrian activity and density distribution. This method further integrated machine learning technology into traditional walkability assessments, surpassing traditional survey methods (Alemdar and Ersoy, 2017; Cogbill et al., 2005; Dasgupta et al., 2014). Morning and evening peaks were prominent in some areas, while in others, activities were more dispersed, reflecting the varying functional orientations of streets. There was a significant positive correlation between the openness of streets, the richness of the streetscape, and street vitality, while narrow street canyon environments tended to suppress pedestrian activity. Through this multidimensional and multi-perspective field research, we were able to characterize virtual street walkability and mobility with actual pedestrian flow and streetscape features.

This study observed the dynamic changes in residents' walking behaviors and lingering patterns at different times of the day, adding a temporal dimension to the analysis of mobility and walkability. The activities of residents were fully documented in aerial and streetscape images, covering data from early morning to evening. The research revealed the characteristics of walking and lingering behaviors during morning and evening peaks, midday breaks, and off-peak periods. For instance, in the streets of UV areas, pedestrian traffic significantly increased during the early morning (6:00-8:00) and late afternoon (16:00-18:00) peak hours, reflecting clear commuting patterns. Conversely, due to different functional orientations, the main street areas maintained a balanced flow of pedestrians, unaffected by peak times. The data also reflected how different functional orientations of streets and surrounding environments impacted pedestrian activities. For example, in the spacious pocket areas of alleys, frequent pedestrian activities indicated that these open spaces provided social and activity spots in narrow street environments. In contrast, pedestrian traffic in market areas was lower than expected, highlighting the limitations of their function or location. Based on this temporal data and model analysis, according to Lai and Kontokosta (2018), the impact of dynamic time changes on street activities was confirmed, emphasizing the importance of considering time factors in analyzing walkability and mobility, consistent with the findings of this study. Through dynamic research methods, a detailed understanding of the complex relationship between street environments and pedestrian behavior was achieved, providing a more timely perspective for mobility research.

6.1.3 Utilizing residents' subjective feedback on UV environment to improve mental well-being and livability (Co-findings from Paper III and Paper I)

Paper I emphasized that livability can enhance the social attributes of streets, primarily by assessing street activities, human-centric environmental design, and residents' willingness to engage in active mobility.

Street activities play a pivotal role in enhancing social interaction and serve as a critical index for assessing neighborhood livability (Sheikh and van Ameijde, 2022). As ideal venues for social integration, streets provide opportunities for residents to engage in street activities both directly and indirectly, creating spaces for ongoing interaction. These accessible and low-threshold activities lay the foundation for long-term contact, highlighting the value of streets as public spaces. Extensive research underscores that factors such as street design, traffic flow, and environmental quality directly impact social interactions and participation among children and adults. Properly designed streets not only offer children opportunities to interact with a diverse range of people and activities but also motivate adults to engage in new activities by observing others (Veitch et al., 2020). The richness and diversity of street activities are crucial metrics for assessing street livability (Kang et al., 2021).

Human-centered street design serves as a key criterion for assessing livability (Figure 6.3). The physical environment of streets influences street activities, and even subtle environmental features can greatly impact the experience of street users. Urban design literature identified several human-centered characteristics that enhance active mobility behaviors, acting as intermediaries between physical features and pedestrian behaviors (Chudyk et al., 2015). Gehl (2013) highlighted that dynamic and static pedestrian activities are vital criteria for determining whether streets are human-centered, emphasizing that the physical environment must support both static and mobile behaviors. Mehta and Bosson (2021) further noted that physical, land use, and social dimensions are crucial for creating streets conducive to lingering, wandering, and socializing. Do et al. (2019) categorized resident behaviors into six types: accessibility, transaction, idleness, service, maintenance, and relaxation, exploring the tripartite relationship among user distribution, behaviors, and the physical environment of streets to promote street

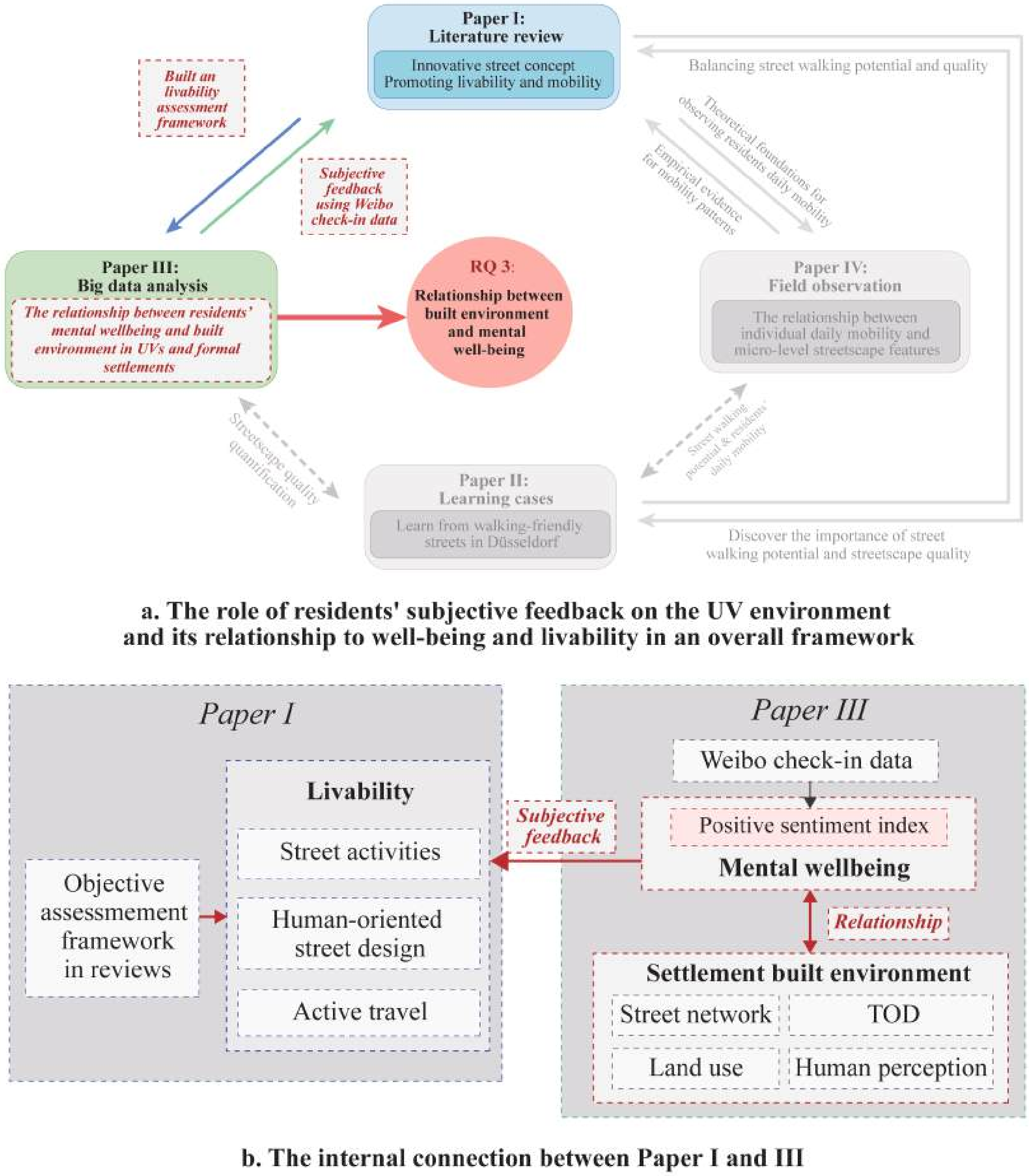

Figure 6.3: (a) The role of residents' subjective feedback on the UV environment and its relationship to well-being and livability in an overall framework; and (b) The connection between Paper I and III.

management and social sustainability. Through an analysis of dense urban streets, flexible street design principles were proposed, including customized usage, multifunctional use, adaptability to changing environments, convenient management, universal usage, and sustainable use. This human-centered street design is not merely a sum of physical components; rather, its integrated effect produces a more notable positive impact than the sum of its parts.

Residents' willingness to actively commute serves as a key indicator for assessing street livability. Streets are inextricably linked to mobility, particularly active modes like walking and cycling. Traditional walkability studies typically rely on field surveys and GIS data analysis (Lloyd et al., 2012; Park and Garcia, 2020). With accumulating theory and advancing technology, measurement methods have diversified. Building on the 3-D (density, diversity, design) theory, Ewing and Handy (2009) expanded it to the 5-Ds (density, diversity, design, distance to transit, destination accessibility) and further developed the 7-Cs standards, including connectivity, convenience, comfort, conviviality, conspicuousness, coexistence, and commitment. These standards overlap with the D variables, forming a multidimensional index system at the street and neighborhood levels.

Assessing street livability often relies on physical indicators such as the richness of street activities, human-centric environmental design, and residents' willingness to engage in active mobility (Rui and Xu, 2024). These physical factors are crucial for enhancing the social attributes of streets, improving residents' interaction and participation. Street activities provide short-term and low-threshold opportunities for participation, helping to establish a continuous interactive environment and highlight the value of streets as public spaces. Human-centered street design goes further by optimizing the physical structure of streets to promote both static and dynamic pedestrian activities, thereby strengthening residents' participation and achieving higher social integration (Wang, 2023). However, residents' mental well-being should also be considered a key indicator for assessing street livability. Although physical indicators reflect the level of street environment and transportation facility design, residents' subjective experiences and mental satisfaction are equally important, as they influence social interactions and mobility choices. Using social media data such as Weibo, residents' emotional expressions, satisfaction, and mobility tendencies can be captured, comprehensively reflecting mental well-being (Zhang et al., 2024; He et al., 2023). This approach provides a subjective feedback-based perspective beyond existing physical dimensions, aiding in a deeper understanding of the actual impact of street design on residents' daily lives (Ma et al., 2024).

By integrating physical indicators with mental well-being data, a more complete framework for assessing street livability can be established. Through the analysis of Weibo data, the application of the PSI demonstrates its importance in reflecting urban mental well-being. Paper III employed NLP technology to assess the mental well-being of residents in FS and UV in Shenzhen, revealing the crucial role of the PSI as an indicator for assessing street livability. Unlike traditional physical indicators, the PSI offers a unique method for capturing residents' subjective feelings, enabling a more comprehensive understanding of the impact of street environments on residents' mental well-being. This method extends from physical to mental indicators, shifting the assessment of street livability from the objective attributes of space to the subjective experiences of residents. By applying NLP technology, the PSI can accurately identify and quantify positive sentiments, achieving high precision (0.98) and high recall (0.95). This technological breakthrough allows for a comprehensive understanding of the mental well-being of residents in different urban areas, thus revealing the impact of variables such as traffic, street density, commercial, and industrial layouts on mental well-being. This complements the research by Shen, Ta (Shen et al., 2021) on the relationship between residential density and residents' mental health.

The study finds that traffic accessibility, street density, commercial density, and transportation service density correlate positively with the positive sentiments of residents in UV, while industrial density and walkability show negative correlations. These results indicate that traffic convenience, commercial facilities, and street designs that cater to diverse residents' needs are crucial factors in enhancing mental well-being and street livability. Additionally, the PSI demonstrates significant spatial heterogeneity between FS and UV, challenging the traditional notion that FS residents have more positive sentiments than UV residents. This finding further proves that urban mobility and the social inclusivity related to transportation costs are closely linked to the positive sentiments of UV residents. Concurrently, the research by Dadashpoor and Keshavarzi (2024) also observed similar social spatial differentiation in their analysis of urban spaces and community dynamics, emphasizing the importance of providing better urban resources to low-income groups as a key aspect of urban policy-making.

Through deep mining of Weibo data, Paper III not only considers mental well-being as a core indicator for assessing street livability but also highlights the need for inclusivity and diversity in urban planning. This enables more effective satisfaction of residents' mental well-being needs, further expanding the dimensions for assessing street livability and constructing a framework that values both physical and mental aspects. This shift from objective spatial assessment to residents' subjective feelings offers new directions for optimizing street design and enhancing urban livability.

6.1.4 The quantitative analysis of daily mobility to enhance the understanding of macro level urban mobility (Co-findings from Paper I and Paper IV)

Evaluating street mobility was crucial for achieving sustainable urban development. By strategically arranging charging facilities and smart infrastructure, a green and eco-friendly transportation system was established (Wu et al., 2020a). Additionally, pleasant street design can encourage outdoor activities and enhance neighborhood cohesion (Butler et al., 2020; Mehta and Bosson, 2021). However, these assessment indicators were often summarized in existing literature as an overall framework, providing directional guidance but lacking in-depth research on specific urban street scenarios (Figure 6.4).

Paper I highlighted that existing research focused on summarizing the macro principles of street network structures, facilities, and design, emphasizing the comprehensive function of streets. However, to formulate more detailed planning recommendations, it was necessary to understand how residents used these facilities and spaces on different types of streets, particularly their specific usage during various times of the day and in different scenarios, as well as the differences in usage patterns among different age groups. The behavioral characteristics of different groups during rush hours, midday breaks, or evening peaks required attention. It was essential to deeply analyze the differences in travel modes and street function choices among residents of different ages, professions, and genders. Furthermore, in terms of street facilities and network structures, identifying aspects that met the needs of different groups and areas that needed improvement was crucial for better street planning recommendations. Research showed that residents of different ages and professions had significantly different functional demands for streets, emphasizing the importance of developing personalized street plans (Shadkam and Moos, 2021; Li et al., 2021b).

Paper IV employed DCNN to analyze the trajectories of crowd activities in four different street areas across various times, revealing differences in street vitality in terms of spatial and temporal distribution. Firstly, in the study's first area, a public space in an UV, pedestrians primarily left and returned to the UV between 6:00 AM to 8:00 AM and 4:00 PM to 6:00 PM, consistent with the rush hour patterns. During

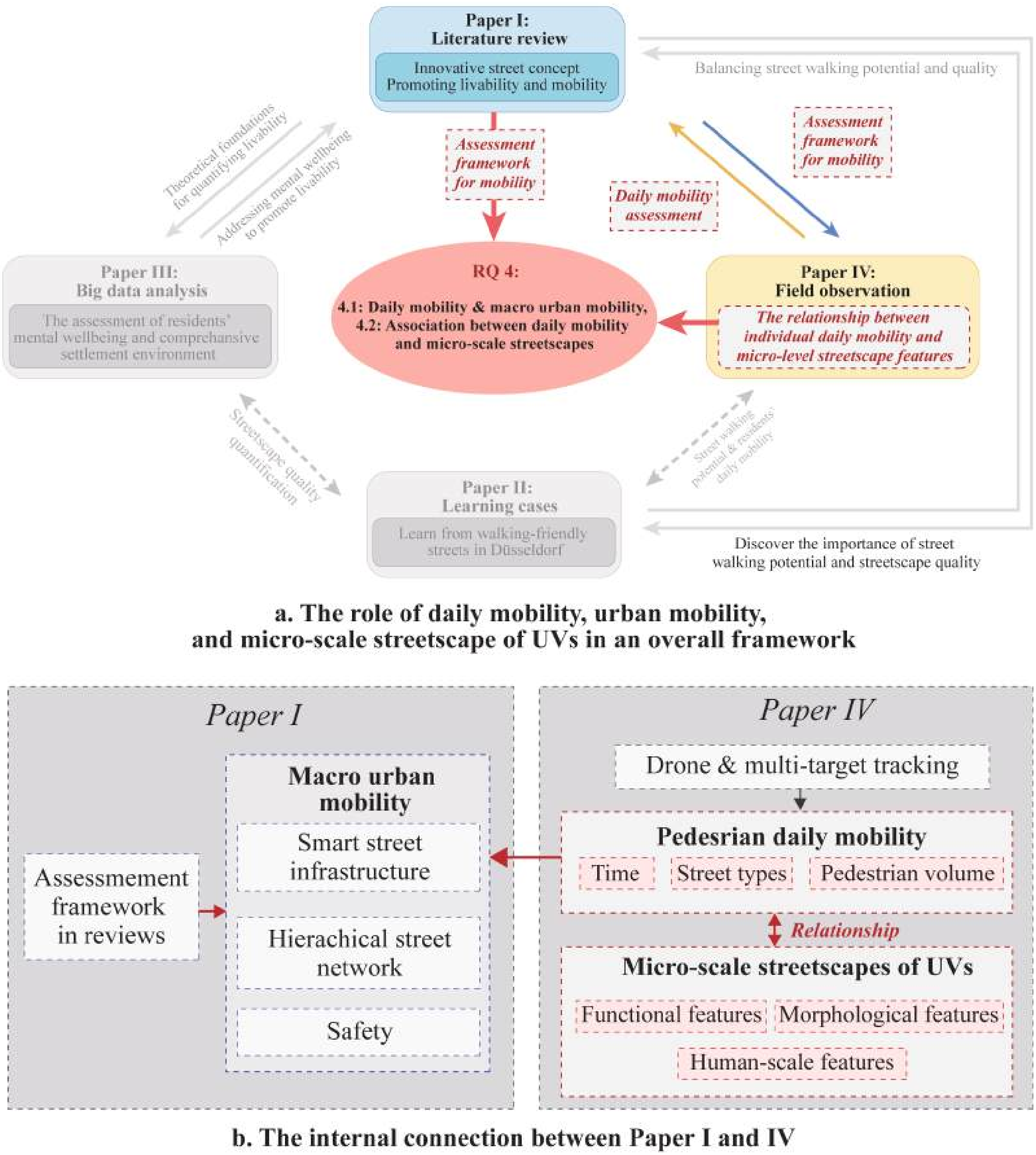

Figure 6.4: The quantitative analysis of daily travel to enhance the understanding of street mobility.

other times, pedestrian trajectories were staggered, reflecting the attractiveness of street commercial activities. In the second area's main thoroughfare, peak times did not significantly affect pedestrians, and differences in pedestrian activity trajectories were minor across different times. Additionally, due to narrow streets, cars and bicycles occupied the sidewalks, forcing pedestrians to walk on the roadway. The third area was a street market, and although it was expected to attract more pedestrians in the morning, the study showed that pedestrian traffic was sparse, with only a few pedestrians active in front of specific shops. The fourth area involved alleyways where pedestrian activity was generally low, but significantly increased in more spacious pocket spaces. Similar findings were mentioned in the study by Sun et al. (2020a), which reported that social interactions occurred more frequently in small streets and pocket spaces within cities compared to broader streets. This indicated that in narrow street environments, pedestrians tended to congregate in relatively wider areas to facilitate social interaction and relaxation (Askarizad and Safari, 2020). Additionally, the results found that bicycles, cars, and pedestrians shared space on the streets of UVs, with pedestrians not strictly adhering to ground markings.

This in-depth observational study, utilizing DCNN technology, provided advantages for evaluating street mobility by revealing detailed distributions of pedestrian activity over time and space, offering tangible data for quantifying street vitality. Compared to traditional macro-planning methods (Alemdar and Ersoy, 2017; Cogbill et al., 2005; Dasgupta et al., 2014), this research more accurately captured pedestrian activities on specific streets and at specific times, revealing the impact of different street types on pedestrian behavior. Moreover, this observational study revealed the direct impacts of specific street facilities and designs on pedestrian behavior, such as forced pedestrian roadway walking on main thoroughfares and the clustering of pedestrians in cul-de-sac spaces, reflecting potential safety and convenience issues in street design (Sun et al., 2020b). Such detailed observations helped identify actual street usage needs among different groups and pinpoint shortcomings in street facility planning.

6.2 Theoretical contributions

In this study, we systematically address four research questions, significantly advancing the theoretical framework and practical application of urban street environment assessment. Each theoretical contribution is linked to a specific research question, ensuring that the research outcomes precisely address these issues.

Firstly, regarding Research Question 1 — How can we access the physical and perception dimensions of streetscape environment? This study developed an assessment system that combines objective indicators with residents' subjective experiences. By integrating GIS data, SVI, and social media analysis, this study offers a new method to comprehensively assess the quality of street spaces, thereby gaining a deeper understanding of how street design impacts residents' behavior and mental health.

Secondly, in response to Research Question 2 — How can we transfer the methodological workflow of streetscape measurement from Europe to Shenzhen? We employed spatial syntax analysis and deep learning technologies to evaluate walkability and pedestrian potential. This approach allows us to precisely analyze the functionality of street networks, particularly how they attract and support pedestrian traffic, providing a scientific basis for the street transformation in the specific context of UVs.

Addressing Research Question 3 — How does the built environment of UVs affect residents' positive sentiments to promote residents' well-being and spatial livability, this study analyzed how various elements of street design, such as greenery, width, and traffic facilities, collectively impact residents' mental responses and neighborhood vitality. Through empirical research, we were able to propose specific strategic recommendations aimed at enhancing the living quality and social interactions in UVs through micro-level transformations of the street environment.

Lastly, regarding Research Question 4 — How does the daily mobility of UV residents contribute to urban mobility, and what is its association with the micro-scale streetscape of UVs? In the theoretical contributions, we primarily addressed the latter, as the former was answered in the final section of the previous chapter. By employing drones and deep learning technologies, this study meticulously captured and analyzed the dynamic changes in the street environment, examining the relationship between micro-scale spatial usage patterns, resident behavior, and physical street characteristics. We used quantitative methods to explore how physical attributes of the streets (such as width, greening, and building layout) influence residents' freedom of movement and street usage efficiency, thereby revealing the specific impacts of these factors on the daily mobility in UVs.

The theoretical contributions of this paper not only systematically respond to the research questions at a theoretical level but also provide new perspectives and practical tools for urban planning and street design, driving urban environments towards more humane and sustainable directions.

6.2.1 Addressing RQ 1: Improving the assessment system of the street from objective and subjective perspectives

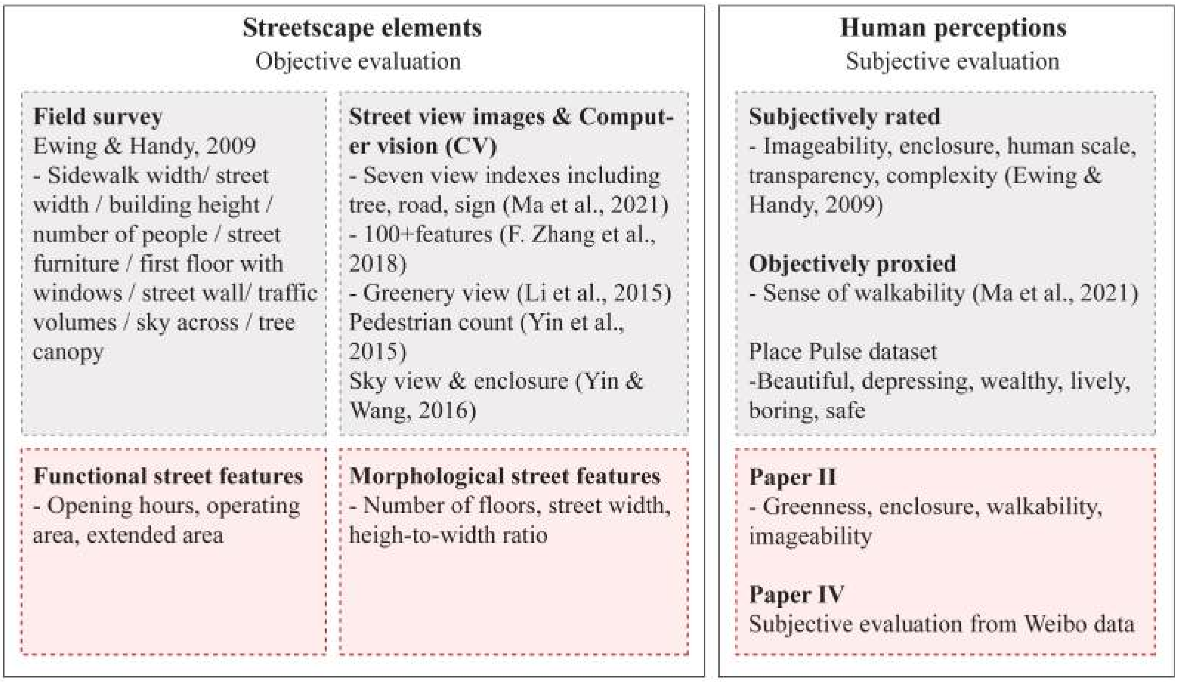

Figure 6.5: Subjective and objective assessment of street space.

There has been limited research in quantitatively assessing the subjective perception of street landscapes on local maps in China. Many important concepts identified in classic urban design research, such as imageability and complexity (Ewing and Handy, 2009), have not been incorporated into the study of UVs. Both subjective and objective indicators are crucial for evaluating street environments. Therefore, in this study, I have expanded the existing literature on quantitative methods for streets by utilizing crowdsourced data and SVI from Shenzhen, as well as Weibo check-in data, to gather local subjective opinions on key street qualities from the urban design literature (Kang et al., 2023).

On one hand, using SVIs combined with semantic segmentation techniques provides a bottom-up perspective, simulating real human street experiences and capturing key features of the streetscape (Table 6.1). Additionally, the data can be updated annually, ensuring continuous monitoring and improvement of urban environments. Semantic segmentation techniques enable precise quantification of features such as street greenery, openness, and enclosure, revealing the relationship between the physical environment and residents' mental responses. On the other hand, using social media data to quantify residents' emotional perceptions offers significant advantages. Residents' feelings and feedback about street environments are directly reflected in their Weibo expressions, providing firsthand insights into actual user experiences of urban spaces (Ghahramani et al., 2021). This method not only saves time and resources compared to traditional face-to-face surveys but also captures more natural, unprompted responses from residents. Sentiment analysis based on Weibo data allows for monitoring and responding to public sentiments about specific environments, complementing objective spatial evaluations (Garcia and Berton, 2021).

This study not only expands the measurement of subjective spatial perceptions but also incorporates functional and morphological street features into the existing objective street space metrics (Figure 6.5). This approach is closely aligned with the latest theories in urban morphology and street functionality. By introducing functional indicators such as business hours and operational area, we can more precisely assess street vibrancy and functional diversity, echoing Jacobs (1961)'s theory on multifunctional neighborhoods. The inclusion of morphological features like building height and street width further aligns the study with Hillier (2007)'s space syntax theory, offering a more detailed quantification of how street morphology can influence behavior. The key advantage of these additional objective quantification standards lies in providing a more comprehensive and accurate tool for analyzing street environments. First, integrating functional and morphological measurements can reveal patterns of street use and functional changes across different time periods, which resonates with Montgomery (1998)'s theory on the space-behavior relationship. Second, the inclusion of morphological characteristics such as the height-to-width ratio allows for the quantification of street "enclosure," a critical concept in Gehl (2011)'s urban design theory for enhancing pedestrian experiences.

Table 6.1: Detailed variables and measurement methods for subjective and objective assessment of street space.

Dimensions	**Indicator Name**	**Definition**	**Measurement Method and Formula**	**Significance**
Subjective assessment of streetscape quality (paper II)	Greenness	The coverage and diversity of vegetation in the street	Calculating the proportion of green pixels in street images	Enhances urban ecological quality, improves resident comfort, and helps mitigate urban heat island effects

Subjective assessment of streetscape quality (paper II)	Enclosure	The degree of spatial enclosure by vertical elements (e.g., buildings, walls) in the street	Calculating the pixel ratio of vertical structures (excluding sky) in images	Affects perceptions of privacy and security, key for creating 'humanized' street environments
	Walkability	The degree to which the street is pedestrian-friendly, including safety and comfort	Calculating the ratio of sidewalk area to roadway and the support from traffic signs and facilities	Directly affects residents' willingness to walk and travel efficiency, indicative of street vitality
	Imageability	The visual attractiveness and richness of the street	Calculating the visual proportion of street elements like signs sculptures benches etc.	Enhances street identity and memorability, increases street attractiveness and commercial value
Objective assessment of functional street features	Opening Hours	The operating times of shops on the street.	Recorded via field observation of each shop's active hours.	Indicates peak activity times and potential for nighttime vitality.
	Operating Area	The physical space occupied by the shop.	Measured in square meters through field surveys.	Reflects the scale of commercial activity and spatial usage.
	Extended Area	Space used by vendors beyond their permanent location.	Observed and mapped in situ to determine the irregular use of public space.	Shows dynamic usage of space which contributes to street liveliness.
Objective assessment of morphological street features	Number of Floors	The number of levels in buildings along the street.	Collected from OSM and verified by field observations.	Influences the street canyon effect and vertical human interaction.
	Street Width	The breadth of the street measured from building to building.	Measured directly or derived from geographic datasets like OSM.	Impacts pedestrian flow and potential for street activities.

	Height-to-Width Ratio	Ratio depicting the proportionate relationship between building height and street width.	Calculated using data from OSM or field measurements.	Affects sunlight penetration and the sense of enclosure on the street.

Our research results demonstrate that subjective perceptions and objective metrics complement each other in evaluating street environments. We found that subjective perceptions are actually closely linked to the physical characteristics of the streets (Ogawa et al., 2024). Objective metrics, such as spatial configuration, greenery, and openness, not only represent the physical dimensions of the street environment but also serve as mediators between subjective perceptions and physical space. Therefore, this study underscores the equal importance of both subjective and objective evaluations, advocating for future research to adopt this integrated perspective to more comprehensively and accurately capture the complex relationships between the physical environment and human perceptions (Qiu et al., 2022). This approach enables a deeper understanding of how street environments influence residents' behavior and mental well-being, contributing to the advancement of urban design and planning.

6.2.2 Addressing RQ 2: Insights from Düsseldorf's street planning on mobility measurement

In Paper II, the calculations of walking potential and walkability employed sophisticated methods. Walking potential was analyzed using sDNA, which considers the connectivity and integration of street networks to reveal their attractiveness to pedestrian flows (Cooper et al., 2021). It assesses the walking potential of a location by measuring the directness and efficiency with which one can reach all other points in the street network from that point. Walkability, on the other hand, was evaluated by integrating the physical and visual attributes of streets, such as the ratio of sidewalks to roadways (Gao et al., 2022). These data were primarily obtained through image segmentation processing of SVIs using the deep learning model DeepLab V3+, and the final walkability score was calculated using specific formulas (Kang et al., 2023). These objective techniques offer a precise and reproducible method for assessing the walking environment. By minimizing subjective human judgment, the accuracy and consistency of the results are ensured. This study comprehensively evaluates the functionality of streets by synthesizing their physical layout, visual properties, and environmental characteristics, particularly through the analysis of visual perceptual quality between GSV and SPPV. This assists urban planners and decision-makers in more effectively allocating resources and implementing pedestrian-friendly street transformations.

Despite the clear methodological advantages of Paper II, it also has some limitations. First, the objective measurement methods used do not consider direct pedestrian feedback, which could lead to an incomplete understanding of the actual use and perception of the streets (Kasraian et al., 2021). Pedestrian subjective experiences and behavioral feedback are crucial for assessing the comfort and functionality of walking environments, and relying solely on image analysis and spatial data may overlook the actual feelings and needs of residents. Secondly, although the study used advanced image processing techniques to simulate and evaluate street environments, it did not conduct cross-validation through field observation. This means the data might lack verification against real-world conditions, affecting the accuracy and reliability of the assessments. Additionally, variations in the timing and environmental conditions of image data collection, such as weather and lighting, could influence the results, and these effects are difficult to accurately assess without field validation (Biljecki and Ito, 2021).

Inspired by the Düsseldorf experiment, Paper IV utilized unmanned aerial vehicles (UAVs, DJI Mavic 2S) and multi-object tracking algorithms (based on YOLO V7 DCNNs, DCNN) to quantify pedestrian flow on streets. UAVs provided the capability to capture street activities from the air, shooting high-resolution videos and images from different altitudes (15m, 25m, 35m, and 60m), with the optimal street coverage view determined at 25 meters. Videos captured by the drones were used to observe the flow and distribution of pedestrians on the streets. Based on this, the YOLO V7 algorithm was used for video analysis, which could rapidly and accurately identify and track multiple targets (such as pedestrians and vehicles) within the videos. By frame-by-frame video analysis for object detection and tracking, and assigning unique IDs to each detected object, it analyzed their movement patterns and activity ranges on the streets (Nagrath et al., 2022).

Employing field research to identify pedestrian flow and street mobility has theoretical significance: first, it allows for a more precise understanding of the relationship between street mobility and environmental features. For instance, using drones and multi-object tracking technology, we can analyze the dynamic relationships between pedestrian volumes and the physical environment of different street types (such as public spaces, main streets, market streets, and alleys). These findings reflect geographical variations in street mobility and are optimized in a data-driven manner. Secondly, this develops a field-based quantitative method for mobility, based on objective measures of walking potential and walkability, thus avoiding biases introduced by objective calculations.

Although this study initially relied on European street environment measurement methods (such as those derived from Düsseldorf), which were considered to be effectively applicable to the environment of UVs in Shenzhen, the findings suggest that this assumption is only partially valid. While complex techniques such as space syntax and deep learning were used to quantify walkability potential, significant differences emerged between various urban environments in terms of actual street usage and residents' perceptions. The high-density residential areas, unique socioeconomic structures, and informal street layouts of Shenzhen's urban villages pose challenges in the accuracy and applicability of directly transferring European standards. However, the use of drone technology and multi-object tracking algorithms provided critical enhancements to address this issue. This approach not only extends and innovates upon European measurement methods but also improves the precision and relevance of mobility assessments. In the complex street environments of urban villages, it effectively captured the dynamic interactions between pedestrian flows and the physical environment. Therefore, the introduction of technological advancements—particularly the use of drones in high-density environments—demonstrates that European measurement methods can still achieve considerable adaptability and effectiveness when appropriately adjusted.

6.2.3 Addressing RQ 3: Streetscape characteristics in UVs affecting residents' positive sentiments and mental well-being

Table 6.2 provides a detailed breakdown of the environmental factors in UVs that influence residents' daily positive sentiments and mental well-being.

Table 6.2: The environmental variables and planning recommendations affecting the mental well-being of UV residents.

Influencing Factors	**Environmental Characteristics**	**Impact on Residents' Positive Sentiment**	**Planning Recommendations**
Transportation & Accessibility	Car Accessibility, Street Density, Public Transport Accessibility	Moderate car accessibility and street density aid in traffic convenience, enhancing positive sentiment; insufficient or overcrowded public transport networks decrease sentiment.	Balance transportation facility density, optimize public transportation networks, reduce parking occupancy to relieve congestion.
Pedestrian Environment	Alleys and Streets Blocking Vehicles	Short-distance pedestrian environments are convenient, stimulating positive sentiment; remote locations prevent residents from meeting daily travel needs through walking alone.	Optimize pedestrian environment with micro and macro-levels in mind, using bike-sharing or micro-electric vehicles as alternatives.
Industrial & Commercial Environment	Industrial Density, Commercial Facilities	Industrial parks' pollution and noise reduce residents' sentiment; commercial facilities offer jobs and social opportunities, strengthening neighborhood belonging.	Reduce industrial density, optimize commercial facility layout to minimize pollution and meet employment and social needs.
Street Density & Economic Structure	Low Street Density, Affordable Housing	Low-density streets provide affordable living environments, promote e-commerce economy, maintain neighborhood harmony and economic transformation, enhancing positive sentiment.	Maintain low street density, ensure affordable housing, promote innovative economic models and diversity.

Public Service Facilities	Schools, Hospitals, Neighborhood Centers, etc.	Inadequate public service facilities can't meet residents' basic needs, reducing happiness and safety.	Construct schools, hospitals, etc., to ensure residents receive essential public services and improve service quality.
Green Spaces & Open Areas	Parks, Green Spaces, Open Areas	UVs usually lack sufficient green and open spaces, affecting residents' leisure and recreation, lowering positive sentiment.	Increase the number of green spaces and open areas, providing more neighborhood parks and activity venues.
Security & Neighborhood Atmosphere	Neighborhood Security, Neighbor Relations	Security issues cause anxiety and insecurity; good neighbor relations enhance belonging and happiness.	Strengthen security management, promote neighbor relationships, organize neighborhood activities to foster inclusiveness and mutual assistance.

Transportation accessibility plays a critical role in the emotional well-being of residents in UVs. My research reveals a significant positive correlation between public transit density, street density, and the density of transportation facilities with residents' positive sentiments. The convenience of the transportation system, especially the dense layout of bus routes, effectively reduces commuting costs, improving residents' travel experiences and overall life satisfaction. This finding is supported by Li et al. (2014a), who demonstrated that improvements in transportation infrastructure contribute to the enhancement of residents' quality of life in UVs. However, my research further emphasizes the particular impact of transportation accessibility on migrant populations, especially in terms of employment opportunities and daily travel options.

In addition, industrial density shows a negative correlation with residents' sentiments. I found that the layout of high-density industrial zones in UVs often leads to environmental pollution, resulting in a decline in residents' quality of life and emotional well-being. This aligns with the findings of Song et al. (2016), who discussed the negative impact of industrial layouts on health and sentiments, particularly concerning air pollution and noise. I further suggest that the implementation of buffer zones between residential and industrial areas can effectively mitigate these negative effects, providing new practical directions for policymakers.

Walkability is another important factor affecting the sentiments of UV residents. Although walking is not a dominant mode of transportation on a macro scale, my research found that the highly connected alley and block networks within UVs offer a high degree of travel flexibility and convenience, which in turn promotes social interaction and community cohesion. Zhang et al. (2022) also explored the relationship between walkable environments and residents' mental health in UVs, showing that walkability has a positive impact on community cohesion and mental health. My research expands on this point by highlighting that in e-commerce-dominated peripheral UVs, walkable environments contribute to economic vitality.

Finally, this study found that UVs with low street density often maintain lower rental rates, providing affordable living spaces for low-income groups and migrant populations. Furthermore, the integration of e-commerce with UVs has enhanced the economic resilience and self-management capabilities of these areas. Some studies (Wu, 2016; Liu and Wong, 2018) have noted that low-rent areas in UVs provide housing options for low-income groups, but they did not delve into the impact of low street density on transportation services. My research complements this by suggesting that, while maintaining low density, optimizing transportation facilities can further improve residents' quality of life.

6.2.4 Addressing RQ 4: Influence of micro level street environment on residents' daily mobility

This research enhances the understanding of how micro-level factors, such as street width, greening, and building layout in high-density residential areas, influence pedestrian mobility through quantitative analysis. While many studies have demonstrated the significant impact of street connectivity and overall transport network layout on residents' walking and travel behavior, they often fail to explore how specific micro-level physical features directly affect mobility. For example, research has shown that higher street connectivity indeed promotes walking behavior, but this conclusion frequently overlooks the direct impact of street width, greenery, and building layout on pedestrian comfort and spatial usage (Knuiman et al., 2014). The findings of this study complement these previous works by revealing the critical role that street width and greening play in shaping pedestrian activity space, offering new insights into street design in high-density urban environments.

This study analyzes the impact of various street elements (such as openness, building density, and traffic infrastructure) on street vitality, further extending research on the relationship between the built environment and mobility. While many macro-level studies focus on the linear effects of land-use patterns on traffic flow, such as the relationship between land use around subway stations and passenger mobility, these studies often overlook the nonlinear effects of micro-level factors like building density or street openness (Gan et al., 2020). By uncovering the complex interactions between open space and building density, this study finds that although openness is strongly positively correlated with mobility, excessive building density may suppress mobility. This finding supplements and challenges the assumptions made in some macro-level studies about the positive effects of high building density (Wu et al., 2021), highlighting that in certain contexts, excessive density may hinder the enhancement of street vitality.

The GBDT model is employed in this research to explore the synergistic and conflicting effects of various street elements, offering a new quantitative approach for analyzing the influence of complex urban environments on pedestrian mobility. Unlike traditional linear models, the GBDT model captures intricate interactions between variables, identifying which environmental factors may amplify or diminish each other's influence under specific conditions. This method enhances the existing literature, which typically focuses on single-factor analysis, and deepens the understanding of the effects of street environments. For instance, the positive correlation between walkability and mobility has been well-established (Hirsch et al., 2017). However, our findings indicate that the complex interplay between openness and building density may, under certain conditions, weaken this positive correlation, revealing deeper dynamic effects.

Table 6.3: Influence of micro level street environment on residents' daily mobility.

Street Type	**Influence**	**Observation results**	**Micro level street environment**
UV Streets	High peak period traffic	Residents mainly enter and exit during peak periods, leading to increased traffic, as the streets connect residential and work areas.	Pedestrian directional signs: Provide clear direction to reduce confusion; Well-planned exits and entrances: Avoid congestion and improve pedestrian flow; Adequate sidewalk width: Ensure a safe and comfortable walking space.
Main Streets	Even distribution of traffic	Main streets connect important areas such as commercial and residential zones, causing a dispersed flow of people, not significantly affected by peak times.	Spacious streets: Allow more pedestrians and vehicles to use the street simultaneously, reducing congestion; Flexible traffic management systems: Adapt to traffic flow changes at different times; Sufficient pedestrian space: Provide a safe walking environment.
Market Streets	Lower than expected pedestrian activity	Although the market has various shops, it may attract fewer visitors than expected due to remote location or unappealing goods.	Shop opening hours: Adapt to customers' shopping times to increase foot traffic; Market layout and functional positioning: Optimize stall distribution to enhance overall market attractiveness.
Alleys	High traffic in specific areas	Alleys are limited in space but have some spacious areas (pocket areas) for rest and social interaction, attracting residents to stay.	Suitable rest and social spaces: Set up comfortable seating and shaded areas to encourage residents to stay; Safe pedestrian paths: Ensure pedestrian safety and reduce conflicts with vehicles.

A series of strategic recommendations for transforming UV streets is proposed, aiming to improve street mobility and inclusiveness through micro-level interventions. These strategies are based on empirical findings and aligned with the objectives set forth in the "Shenzhen UV Comprehensive Improvement Master Plan (2019-2025)" and the "14th Five-Year Plan for New Urbanization (2021-2025)." By addressing the relationship between micro-physical environments and mobility, this analysis expands on existing planning frameworks. For example, while previous studies have emphasized the role of functional mix and transportation infrastructure in UVs, our study reveals that incorporating greenery and resting spaces contributes uniquely to improving residents' quality of life and fostering social interaction, thereby enhancing street vitality. This insight contrasts with Wu et al. (2022)'s macro-level analysis and enriches our understanding of the effects of greening and resting spaces at the community level. Even in dense UVs, modest increases in green and social spaces can significantly boost street vitality and strengthen residents' social cohesion, challenging the neglect of greening functions in high-density environments noted in previous literature.

Drone technology and DCNNs are integrated into this research, replacing traditional manual observation methods and overcoming the limitations of static data collection. Compared to conventional methods, this approach dynamically and accurately captures spatiotemporal behavioral changes on streets, offering new insights into mobility formation at the micro-scale. This technical pathway challenges traditional frameworks based on static data, particularly in highly dynamic UVs, where deep learning technology excels in identifying and quantifying behavioral patterns with greater precision (Zhang et al., 2019). As a result, this methodological innovation not only advances urban mobility research but also provides a modernized foundation for future studies.

The theoretical and practical contributions of this research further the understanding of street design and planning in high-density informal settlements. By presenting specific case studies, the research demonstrates the practical effectiveness of micro-level interventions in enhancing mobility and inclusiveness. While much of the existing literature focuses on macro-scale urban renewal and community reconstruction, our analysis of different types of UV streets reveals significant variations in the impact of street design on mobility. This challenges assumptions in some macro-level studies that high building density necessarily suppresses vitality (Dong et al., 2020). Through more nuanced street-level interventions, this research offers detailed theoretical and practical guidance for promoting sustainable development and creating inclusive urban environments in UVs.

Table 6.3 systematically organizes the impact of the micro-level street landscape on residents' daily commutes, categorizing and discussing the variations in the impact of four different types of UV streets on residents' daily mobility.

6.3 Planning implications

6.3.1 Spatial optimization strategies

Transformation of economic models in UV Streets

The economic model of UV streets is transitioning from traditional small shops and street vendors to online economies, such as developing into "Taobao Streets" or "Creative Arts Streets." By leveraging the flexible spatial layout and low rental costs of UV streets, local residents and migrant workers can directly sell products to national and even global markets through e-commerce platforms. This not only broadens sales channels but also significantly enhances the economic vitality of the streets and the income levels of residents.

This transformation also drives the improvement of street infrastructure, such as enhancing internet access, establishing express logistics stations, and renovating public spaces on the streets, providing better support for both online and offline commercial activities. Furthermore, the widespread use of e-commerce has led to digital skills training and enhancement for residents, further improving their employment opportunities and quality of life.

Optimizing street networks and pedestrian accessibility

Informal settlements typically feature a dense street network, but at a larger spatial scale, some streets can be excessively narrow, hindering residents' mobility. Thus, it is advisable to maintain a well-connected pedestrian network within UVs to enhance pedestrian accessibility at a micro level. However, the street network around UVs should not expand excessively to retain the characteristics of low rent and affordable housing, supporting the e-commerce economic model. In FSs, optimizing the pedestrian network is equally crucial to create a "15-minute living circle," ensuring convenient and safe neighborhood living while reducing traffic noise and air pollution to protect residents' physical and mental health.

Building proportion and road width

In terms of enhancing street openness and width, our research further reveals the relationship between the proportion of buildings in the visual field and street vitality. Specifically, when the visual proportion of buildings is less than 55%, there is no significant change in street vitality values. However, when this proportion is between 55% and 65%, street vitality shows an upward trend; when it exceeds 65%, vitality consistently decreases. This indicates that an appropriate spacing and proportion of building elements, between 55% and 65%, helps support pedestrian activity, while excessively dense building clusters or overly open urban environments are less conducive to pedestrian experiences.

Based on this finding, in the transformation of streets in informal settlements, it is crucial to widen the width of main streets and enhance overall street openness. Reducing the obstruction caused by overly tall buildings to ensure adequate lighting and ventilation can optimize the environmental experience for pedestrians and commercial activities. Additionally, appropriately widening streets not only helps accommodate diverse activities and pedestrian flows but also provides opportunities for businesses to expand their operating spaces, promoting positive interaction between commerce and public spaces. Compared to previous studies (Yin and Wang, 2016), our research provides empirical evidence on the relationship between current urban form and the street canyon effect, emphasizing the importance of building proportions in street design.

Maintaining street diversity

Maintaining the diversity of street commercial functions can extend its influence and provide convenience to larger urban areas. This diversity allows for the accommodation of various types of businesses, from retail shops and food vendors to artisans and service providers, thereby attracting a wider array of customers and visitors. By integrating multiple commercial functions, streets can become bustling hubs that serve not only the local community but also attract people from across the city.

Additionally, the diversity of street furniture and elements not only enhances the aesthetic appeal of streets but also effectively attracts residents to linger and participate in activities. To meet the needs of different functional areas, facilities such as benches, streetlights, trash bins, and signage should be added. In commercial or market areas, considerations should be given to installing canopies, stalls, and display racks to provide merchants with convenient expansion facilities. The flexible and diverse nature of street furniture and elements can improve the functionality and livability of streets while fostering a vibrant commercial atmosphere.

Incorporating multifunctional spaces and interactive elements can further enrich the street environment. For instance, integrating playgrounds, small green spaces, and public art installations can create areas suitable for people of all ages. Additionally, combining digital elements, such as interactive kiosks and free Wi-Fi hotspots, can modernize the streetscape and cater to the needs of a tech-savvy population.

Planning internal and external traffic flows in UVs

To enhance the overall functionality and quality of life in UVs, it is crucial to plan traffic flows effectively. By increasing public transportation facilities in the external areas and implementing traffic calming measures internally, traffic conditions can be improved, creating a safer and more livable community environment.

Firstly, public transportation facilities, including bus stops, metro stations, and shared bicycle stations, should be added to the external areas of UVs. These facilities provide residents with convenient travel options, reducing reliance on private cars, and consequently decreasing traffic congestion and environmental pollution. Encouraging residents to use public transportation can improve overall traffic efficiency and promote sustainable urban development. Secondly, traffic calming measures should be implemented in the internal areas of UVs, similar to the concept of "superblocks." These measures include setting up speed bumps, pedestrian zones, bicycle lanes, and areas where private cars are prohibited. The aim is to reduce vehicle speeds, minimize traffic accidents, and enhance the safety of pedestrians and cyclists. Additionally, green belts and public spaces can be added to provide residents with more leisure and activity areas.

This integrated approach to traffic planning, combining both internal and external strategies, can optimize traffic flows and enhance the functionality of UVs. It also creates a safer, more comfortable, and environmentally friendly community environment. By planning traffic flows effectively, residents' travel experiences will be significantly improved, and UVs will become more vibrant and livable.

Green spaces and public areas

In high-density UVs, adding green spaces requires careful planning to avoid making streets more congested. First, street trees and flower beds can be appropriately added to wide streets and open spaces. This not only provides shade and beautifies the environment but also improves air quality. Second, small parks or activity spaces can be created in secondary streets or pocket areas. These spaces do not require much land, but with clever design, they can provide residents with recreational areas. Fitness equipment, children's play facilities, benches, and pavilions can be installed to meet the needs of residents of different ages. These public spaces can also promote social interaction among community residents, enhancing community cohesion. Moreover, street greenery should fully consider the needs of pedestrians and cyclists. Sufficient pedestrian walkways and bicycle lanes should be reserved to avoid excessive occupation of road space. At the same time, green belts can serve as buffer zones, enhancing traffic safety and comfort. Walkways and bicycle parking areas can also be set up to facilitate residents' travel.

6.3.2 Neighborhood engagement strategies

Encouraging moderate expansion of commercial spaces

In the redevelopment of UV streets, it is crucial to integrate the concepts of buffer space and flexible streets to achieve a balanced expansion of commercial areas. While commercial facilities can invigorate the street environment, this must be managed through meticulous planning and regulation. Within this framework, shop owners can be permitted to utilize the buffer space in front of their establishments for outdoor displays, seating, and other facilities, enhancing the commercial atmosphere of the street through adaptable arrangements.

These buffer spaces exhibit temporal and spatial flexibility, allowing for dynamic adjustments based on different time periods and usage needs. For instance, during peak hours, the usage area for outdoor facilities can be moderately restricted to ensure smooth pedestrian flow and prevent congestion. Conversely, during off-peak hours, the utilization of buffer spaces can be relaxed, providing businesses with more room for display and interaction. Such dynamic adjustments not only optimize the street's usage efficiency but also facilitate a symbiotic relationship between commercial activities and pedestrian movement.

Implementing a well-structured management strategy for operating hours is also essential to fully exploit the street's commercial potential. On this basis, the commercial activities within these communities can radiate outward, satisfying the diverse needs of local residents while fostering economic interaction among different social groups. This approach ultimately enhances the overall vibrancy and sustainable development of UV streets.

Adopting micro-renovation planning

Micro-renovation plans for streets should meticulously consider the daily needs of neighborhood residents and devise practical strategies through participatory planning. Involving residents in the planning and design process can enhance their sense of belonging to the neighborhood while ensuring that street renovations genuinely address practical needs. By flexibly adjusting the layouts of public spaces and commercial areas, micro-renovation plans can optimize street functionality with minimal disruption to existing structures.

Policymakers as advocates of participatory planning

At the governmental level, policymakers should proactively advocate for participatory planning by inviting residents to be involved in neighborhood redevelopment planning and design. Active resident participation not only ensures that renovation plans align with actual needs but also bolsters residents' sense of neighborhood belonging and cohesion. This process can be facilitated through neighborhood meetings, surveys, and focus groups to ensure that residents' perspectives are reflected in the renovation plans.

Leveraging the historical and cultural value of UVs through publicity and education can improve residents' positive perceptions of these villages and reduce societal biases, thereby fostering more inclusive social integration. Organizing cultural festivals, exhibitions, and artistic events that merge historical and contemporary development provides residents and outsiders with opportunities to better understand the villages while promoting cultural interaction and exchange across neighborhoods. Additionally, policymakers should collaborate with social organizations and nonprofits to conduct workshops, seminars, and volunteer activities that increase residents' social engagement, empowering them to have a stronger voice in neighborhood affairs and fostering an inclusive and vibrant neighborhood environment.

6.3.3 Functional development strategies

Prioritizing public transportation development

In all informal settlements, prioritizing the development of public transportation (such as buses and subways) can enhance residents' commuting experience and reduce reliance on private vehicles. By constructing a rapid and reliable transit network, traffic congestion can be alleviated, commuting times shortened, and street space conserved, thereby mitigating air pollution and noise. Compared to private vehicles, public transportation offers greater accessibility and convenience while providing an affordable mode of travel for low-income groups.

Enhancing commercial and public facilities

Increasing the density of commercial zones in FSs and providing more opportunities for socialization and employment can instill a stronger sense of neighborhood belonging among residents. The development of commercial areas should be aligned with pedestrian network designs, ensuring accessibility between shops and residential areas. In UVs, the flexible planning of commercial zones should align with the "One Village, One Product" economic model to maintain the advantages of the e-commerce economy and provide ample employment and economic opportunities for low-income residents.

Proposing differentiated housing policies

Housing policy adjustments should be tailored to the unique circumstances of different UVs through differentiated strategies. UVs located in city centers or core areas, due to their advantageous geographical locations and high rents, should rationally plan baseline floor-area ratios. By adjusting land prices and utilization strategies, rental costs can be controlled at reasonable levels to provide affordable housing options for low-income groups. Economic housing policies could be piloted in appropriate areas to meet the housing needs of more low-income residents, in conjunction with the unique economic model of UVs.

Moreover, the government should encourage long-term collaboration between UVs and urban industrial capital, incorporating UVs into the urban production structure through integrated industrial chains. UVs can be transformed into small-scale economic zones to enhance productivity and economic prosperity. UV redevelopment policies should also consider providing equitable distribution plans for affordable housing to residents across different income groups, ensuring fairer allocation of resources and broader housing choices.

6.4 Research limitations

6.4.1 Limitations of UVs in representing informal settlements

This study focuses on UVs in China as a notable social phenomenon in the process of urbanization, particularly exploring the impact of their spatial structure on the mental well-being and daily mobility of residents. However, in taking UVs as representative cases for the study of informal settlements, we must recognize several key limitations.

The uniqueness of UVs as a subject of study is primarily determined by specific geographical locations and cultural backgrounds, limiting the broad applicability of research findings. Taking Shenzhen as an example, the city's bordering with Hong Kong and its geographical position at the core of the Pearl River Delta Greater Bay Area provide Shenzhen with unique geopolitical advantages and economic integration opportunities. This geographical advantage not only promotes Shenzhen's rapid economic growth but also gives rise to a unique UV phenomenon, which may be difficult to find direct counterparts in other global cities (Hao et al., 2011; Al et al., 2014). At the cultural level, UVs in Shenzhen reflect the population migration and social changes under China's rapid urbanization background. These UVs, while undergoing gentrification, not only display cultural diversity and social vitality but also reveal the social contradictions and challenges in the urban development process (Zhan, 2021). In contrast, informal settlements in other parts of the world, although also facing the challenges of rapid urbanization, have different backgrounds of formation, resident compositions, and cultural characteristics, deeply influenced by their respective countries' historical processes, cultural traditions, and social structures (Huchzermeyer et al., 2014; Del Mistro and A. Hensher, 2009). For example, the slums in Latin America [196], shantytowns in Africa (Richards et al., 2007), and UVs in India (Shirgaokar and Rumbach, 2018), although all forms of informal settlements, reflect their respective different geographical environments, economic conditions, and cultural backgrounds.

Secondly, the urbanization process itself displays different development speeds and characteristics in various regions. Although Shenzhen's urbanization started later, within a mere 40 years, leveraging its special status as an Economic Zone, Shenzhen has leaped from a fishing village to a modern international metropolis (Campanella, 2008). This rapid development speed and unique urbanization model, while providing important cases for understanding the adaptation and transformation of informal settlements under rapid urbanization, face specific challenges and strategies that may not be applicable to other cities developing at a slower pace or at different urbanization stages. UV case studies can provide deep insights into the adaptation and transformation of informal settlements under rapid urbanization, but their unique development paths and coping strategies may be difficult to apply to informal settlements under different cultural and socio-economic backgrounds.

The applicability of policies and planning strategies presents limitations in the study of UVs as representative cases of global informal settlements. The Chinese governance strategy for UVs has undergone a transition from large-scale demolition and reconstruction to refined, humanized transformation, reflecting increasing attention to residents' quality of life and sustainable neighborhood development (Liu and Li, 2021). Over the past decade, policies have shifted from emphasizing large-scale demolition and new construction to more refined transformations that protect the original neighborhood structure and culture while introducing modern facilities and services. In some suburbs, UVs have promoted the integration of living and working through the introduction of small economic zone models, forming a new type of UV that satisfies both economic development and social stability (Lin et al., 2011). These governance strategies and transformation practices, while achieving considerable success in China's specific political and economic context, face challenges in their applicability globally. The legal systems, political environments, and socio-economic needs of different countries vary significantly, especially in regions like Southeast Asia and South Africa, where the core issues and challenges faced by informal settlements governance strategies may fundamentally differ from those in China's UVs. For example, informal settlements in Southeast Asia often relate closely to land ownership disputes, infrastructure deficiencies, and environmental pollution (Dovey and King, 2011), while those in South Africa face challenges of poverty, unemployment, and social inequality (Brown-Luthango et al., 2017).

Although the transformation and management strategies of Chinese UVs provide an important reference framework for urban planning and informal settlements governance, their application in other global regions requires careful consideration of local conditions. This calls for urban planners and policymakers to fully consider legal, cultural, economic, and social differences, as well as the customized and adaptive measures that must be taken, when promoting and implementing these strategies. Moreover, interdisciplinary research and international cooperation play a key role in sharing experiences, adjusting strategies, and innovating solutions, helping global cities to respond more effectively and sustainably to the challenges of informal settlements.

6.4.2 The lack of longitudinal spatial assessment

This study employed open data sources such as Weibo text data, POI, and street and building footprint data to quantitatively analyze the diversity of UVs, the relationship between residents' mobility and streetscape landscapes, and the impact of the street environment on residents' well-being. However, we must acknowledge the limitations in conducting longitudinal spatial assessments.

Our research methods, including the analysis of pedestrian dynamics on streets at different times of the day in Publication IV, represent an attempt to observe short-term changes. This approach provided us with a micro-scale temporal dynamic perspective, aiding our understanding of variations in daily street use patterns. Yet, this method limits our ability to capture and comprehend long-term changes. As dynamically evolving socio-economic entities, the physical characteristics and demographic composition of UVs undergo continuous transformations due to seasonal variations and annual development (Wang et al., 2009). These long-term trends are crucial for a comprehensive understanding of the evolution of UVs (Chung, 2010). Particularly over extended time scales, seasonal changes can significantly affect the street environment and resident activities, such as the impact of climate conditions on residents' daily commutes and social activities (Ji et al., 2024). Moreover, over the years, the physical environment and social structure of UVs might experience profound transformations. For instance, over the past 20 years, UVs have transitioned from neighborhoods predominantly composed of local residents to those primarily inhabited by migrant workers (Pan and Du, 2021). Such demographic shifts not only affect the socio-economic characteristics of the neighborhood but may also alter how residents utilize and perceive street spaces. The lack of longitudinal micro-studies means we might fail to fully capture these changes, leaving blind spots in our understanding of internal structural changes, the evolution of residents' quality of life, and the transformation of relationships with the external urban area. This limitation not only restricts our grasp of the comprehensive picture of UV transitions but may also lead to overlooking critical socio-economic dynamics and changes in residents' sentiments.

6.4.3 The gap between the singular perspective on streets and the overall spatial enhancement

This research has demonstrated that streets serve not merely as conduits for passage but as vital links connecting various spaces and functions within the neighborhood, facilitating interaction and integration between different areas. Therefore, in the spatial transformation of UVs and informal settlements, it is crucial to adopt a holistic and systemic perspective, recognizing the synergistic effects between street spaces and other public spaces. For instance, the complementary relationship between streets and retail spaces can boost economic activities and social interactions, while synergy between streets, public entertainment spaces, and green areas can enhance residents' quality of life and the sustainability of the neighborhood environment. By considering the functions and designs of streets in conjunction with other spaces, a more comprehensive and coordinated improvement of the neighborhood environment can be achieved. Future research should pay greater attention to this cross-space synergy, exploring how the organic combination and complementarity of streets with other public spaces can be leveraged. Approaching the spatial transformation and planning of UVs or informal settlements solely from the perspective of streets may overlook the overall complexity and dynamics of these spatial relationships (Agarwal, 2002). Such a singular viewpoint could lead to inadequate planning, failing to fully exploit the potential of various spaces and, consequently, impacting the comprehensive development of UVs and the overall welfare of residents. For example, failing to consider the synergistic effects between streets and other spaces might limit the efficiency of public space usage, weaken neighborhood cohesion, and even exacerbate internal neighborhood conflicts due to unresolved potential conflicts (Grodach, 2010). Thus, spatial planning for informal settlements requires a more comprehensive perspective, taking into account the interactions and synergistic potential between streets and other spaces, to optimize the neighborhood environment and enhance the quality of life for residents.

Additionally, an important research limit exists in the isolated consideration of internal streets within UVs, without adequately accounting for their close connection to the bstreeter urban street system (Sucher, 2010). This fragmented perspective may impede the optimization of street space and the enhancement of the overall neighborhood environment. The isolation of UV internal streets and their lack of coordination with the city's street system significantly reduce the neighborhood's accessibility and internal mobility. This limited mobility not only restricts residents' access to external urban services and resources but may also exacerbate internal economic segregation and social exclusion within the neighborhood (Wang et al., 2009). From an environmental perspective, the discordance between UV internal streets and the city street system may disrupt the continuity of urban green spaces and public areas, hindering the formation of urban ecological networks and the protection of biodiversity (Wu et al., 2020a). Furthermore, the lack of coordination between UV internal streets and the city street system may also affect the overall image and attractiveness of the city. The city, being an organic whole, sees its overall functionality, aesthetics, and residents' quality of life impacted by the planning and management level of streets and public spaces within UVs, as integral parts of the city.

6.5 Further questions and research frontiers

UV research often falls within the realm of sociology due to its close association with themes such as population migration, gentrification, and neighborhood segregation. An important shift that is emerging but requires further action is to integrate spatial planning into UV research and recognize it as part of urban renewal and sociology. As potential answers to these questions, spatial aspects of UVs encompass several research frontiers, as outlined in Table 6.4, including:

- Transportation and parking behavior of UV residents
- Spatial emotional atmosphere and public participation in decision-making
- Distribution and equity of green spaces in UVs
- UV classification based on image multimodal fusion
- Spatial inclusivity and redevelopment models of UVs
- Assessment of public and private space boundaries in UVs

Table 6.4: Research frontiers and their respective remarkable works.

Research frontiers	Representative works
Transportation and parking behavior of UV residents	(Yu et al., 2019; Li et al., 2024)
Spatial emotional atmosphere and public participation in decision-making	(Tan et al., 2019; Wang et al., 2024)
Distribution and equity of green spaces in UVs	(Xu et al., 2024)
UV classification based on image multimodal fusion	(Chen et al., 2022a,b)
Spatial inclusivity and redevelopment models of UVs	(Li et al., 2021a; Wu et al., 2020b)
Assessment of public and private space boundaries in UVs	(Van Oostrum, 2022; van Oostrum, 2020b)

Table 6.5: Further questions remaining to be addressed through UV research.

Further questions remaining to be addressed through UV research.
1. Can the fusion of satellite and street-view images in UVs more accurately identify different building types and street layouts? How can this classification method aid in solving the unique management needs of UVs in urban renewal and planning?
2. How can remote sensing and social sensing data be used to accurately capture the diverse lifestyles in UVs? What specific social, economic, and spatial characteristics of UVs can these data reveal?
3. How can inclusive redevelopment models ensure that vulnerable groups in UVs are not marginalized during reconstruction? How can this strategy balance the rights of migrant populations with overall urban development needs?
4. How are parking choices in UVs affected by building density and traffic management? Do current parking strategies meet the diverse needs of residents?
5. Can market-oriented renovation models improve overall resident satisfaction in UVs? Which factors most impact resident satisfaction during the renovation process?
6. What role do informal alleyways play in the spatial distribution within UVs? How does this encroachment affect residents' use of public and private spaces?
7. How can the reuse of public spaces and temporary facilities in UVs improve residents' quality of life? How does this transformation contribute to enhancing neighborhood vitality and inclusivity?
8. How can the creation of an emotional atmosphere in UV renovation stimulate public participation? How does this atmosphere ensure that residents feel a sense of identification with the renovation plan?
9. How can UV governance balance inclusiveness with urban service boundaries? How do current governance models affect the rights and access to services of different stakeholders?
10. What differences exist between UVs and residential areas in the distribution and accessibility of green spaces?
11. How does the built environment of UVs influence residents' travel modes and commute times? How should planning departments adjust transportation strategies to meet the actual needs of UV residents?

The frontiers outlined in Table 6.4 are crucial for future research and are expected to garner widespread attention. Whether serving as a position statement for city managers/administrators, landscape planners, urban planners, scientists, and stakeholders in UV spatial planning to provoke further discussion, or as a showcase for broadly applying the concept of urban renewal in diverse contexts, these topics warrant continued focus. Future research should continue to explore these frontier themes. In future studies, the further questions listed in Table 6.5 should be considered, along with potential responses to these issues.

In conclusion, this thesis defines innovative UV street research as a planning concept aimed at providing multifunctional and well-connected street infrastructure for informal settlements and residents in the context of rapid urbanization. As a spatially-based approach, this thesis reinforces UV street infrastructure as a planning concept that transcends traditional land use and urban planning to enhance the mobility, sustainability, and quality of life for UV residents.

Chapter 7

Conclusions

7.1 Proposing the innovative street concept in UVs

This study introduces the concept of innovative streets within UV environments, aiming to transcend the limitations of traditional street research and provide a multidimensional, multifunctional integrated strategy for street space design and optimization (Figure 7.1). Traditional research often focuses on static quantitative indicators to evaluate street environments (Poon, 2017; Li et al., 2014a). However, this one-dimensional analysis overlooks the complexity of streets as dynamic interactive spaces and fails to reveal the interactive relationship between the street environment and resident behavior. Therefore, we propose the concept of innovative streets, offering a new perspective and solution for street environments in UVs.

The core of innovative streets lies in emphasizing the synergistic effects of multiple spatial variables, including the integration of physical, social, economic, and health dimensions. Based on resident-led planning principles, streets are not only traffic corridors but also vital platforms for resident interaction, social engagement, and commercial activities (Umstattd Meyer et al., 2021; Mehta and Bosson, 2021). This multidimensional, multifunctional design not only considers the macro physical characteristics of streets but also focuses on the micro-scale interaction between streetscape elements and resident behavior, thereby promoting efficient utilization of street spaces. For instance, by advocating for pedestrian-oriented streets in UVs, in line with traffic calming measures in superblocks, increasing diverse street elements to enhance spatial attractiveness, and improving street openness and width where possible, it meets the needs of ground-level commercial expansion and visual freedom. This resident-centered street transformation concept helps transition traditional streets from single-function spaces into urban spaces with diverse interactivity (Hao et al., 2012).

Notably, data-driven approaches are key in the concept of innovative streets. Traditional research mainly relies on surveys and interviews (Dasgupta et al., 2014; Veitch et al., 2020; Kasraian et al., 2021), which are static and insufficient in capturing the dynamic changes of streets. In contrast, innovative streets incorporate advanced measurement technologies such as drone technology combined with object tracking and eye-level street landscape assessment to monitor and analyze street usage in real time. This approach not only improves data collection efficiency but also provides more accurate and insightful data support for street design, effectively identifying street changes at different temporal and spatial scales and emphasizing dynamic assessment and optimization of street environments.

Furthermore, the concept of innovative streets places a high emphasis on residents' daily active travel and mental health. Streets, as venues for social interaction and cultural production, are designed to enhance residents' physical health, mental well-being, and sense of community belonging. By transforming

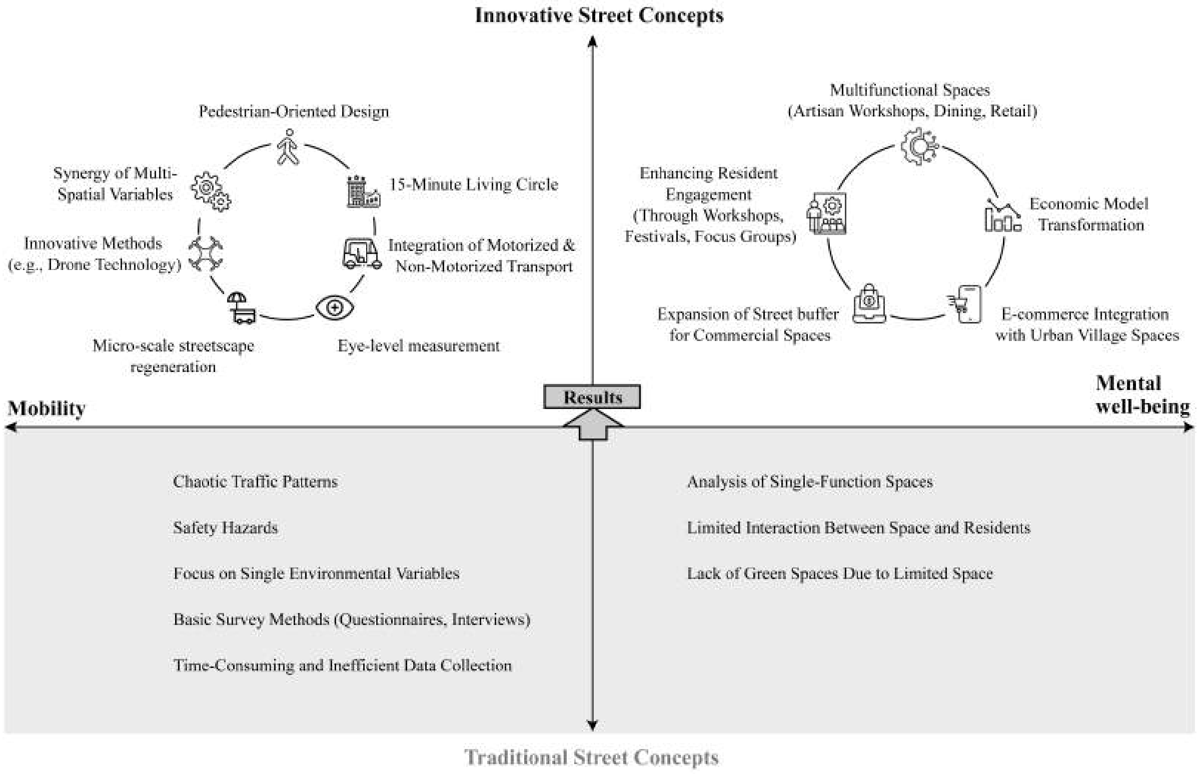

Figure 7.1: The application of innovative streets in UVs and the reshaping of traditional streets.

UV streets into pedestrian-friendly and safe spaces, it encourages residents to participate in daily activities and social interactions, injecting vitality into the community (Askarizad and Safari, 2020). This not only aligns with environmental psychology research on "environmental benefits" (Mertens et al., 2016; Miller et al., 2022) but also corresponds with urban sociology theories on the impact of space on social interaction. Through resident participation, commercial expansion, and social activities, innovative streets not only improve the physical environment but also enhance the social function of the community, increasing residents' sense of identity and satisfaction with the street environment.

From a practical perspective, innovative streets offer concrete and feasible transformation strategies for UVs. By expanding street space for commercial activities, they enhance the vitality of street-facing businesses. Through resident participation and community activities, they strengthen the social functions of the streets. Additionally, by integrating e-commerce with UV spaces, they stimulate regional economic vitality. These practical measures not only improve the physical environment of UVs but also effectively alleviate the issue of single-functionality caused by spatial constraints, fostering multifunctionality and diverse interactivity in street spaces.

Overall, the concept of innovative streets offers a new theoretical framework and practical path for improving the street environment in UVs. Through the collaborative design of multiple spatial variables, data-driven dynamic analysis, and attention to residents' daily activities and mental well-being, innovative streets are expected to transform UVs from areas with single functions and chaotic environments into multifunctional, interactive urban spaces, thereby enhancing residents' quality of life and community well-being.

However, a critical question that arises is whether we truly need "Innovative Streets." Given that UVs in Shenzhen and other areas (such as Guangzhou) are undergoing large-scale government-led transformations, with some even becoming popular social media hotspots, this question is particularly relevant. The answer provided by this study is: to some extent, it is necessary. First, while some UVs in Shenzhen and Guangzhou have been redeveloped, the phenomenon of UVs continues to emerge in other rapidly developing Chinese cities. This is a long-term issue tied to the pace of urbanization and development, and even in the case of temporary transformations, UVs may persist for decades. Therefore, the "Innovative Streets" concept proposed in this study holds broader applicability, offering planning insights for other high-density residential areas. Second, although some UVs have been transformed into popular tourist spots, the question remains: is this transformation truly aligned with the needs of the residents? In many cases, it may not be. The concept proposed in this study focuses on enhancing residents' health and well-being, rather than catering to fleeting social media trends, making it more closely aligned with the genuine needs of the local community.

It is important to note, however, that as the transformation of UVs progresses and residents' needs evolve, the "Innovative Streets" concept must also adapt accordingly. This implies incorporating more inclusive planning approaches, utilizing more advanced and comprehensive quantification methods, and grounding the framework in thorough field research. In doing so, it can provide new insights and solutions for other high-density and informal settlements.

7.2 Main contributions

This dissertation makes significant contributions to the field of urban planning by addressing critical gaps and proposing innovative solutions to enhance the street environments of UVs in China, with broader implications for informal settlements globally. In response to the identified research questions, the study systematically explores the multifaceted aspects of street environments through a comprehensive methodological framework that integrates both subjective and objective assessments. It provides a nuanced understanding of the physical and perceptual dimensions of streetscapes (RQ1), transfers methodological insights from European contexts to Shenzhen (RQ2), examines the impact of built environments on residents' positive sentiments and well-being (RQ3), and elucidates the association between daily mobility and micro-scale streetscapes in UVs (RQ4). The contributions are delineated through four key areas: the transformation of streets in informal settlements, the integration of qualitative and quantitative measurements, the establishment of comprehensive indicators for macro and micro street environments, and the combination of objective and subjective perspectives. These contributions not only offer theoretical insights but also provide practical guidelines for urban planners aiming to create inclusive, livable, and sustainable urban environments.

7.2.1 Focus on the transformation of streets in Chinese informal settlements

In the process of rapid urbanization in China, informal settlements such as UVs are often viewed as peripheral areas within urban development, and the challenges they face have not received adequate attention or effective research. However, these areas play a critical role in housing, economic activities, and social structures. Research into the transformation of streets in these informal settlements is not only a remarkable topic within urban planning and social sciences but also key to exploring how improvements to infrastructure and public spaces can enhance the overall functionality and living conditions of cities. This dissertation focuses on the academic contributions of street transformation in informal settlements in China in terms of enhancing the quality of life for residents, economic vitality, and social and cultural integration.

Addressing the shortcomings in current research perspectives

Contemporary urbanization studies often focus on macro urban development and planning policies, with less in-depth analysis of informal settlements. These areas, particularly UVs, provide low-cost housing and essential social services that are vital for the city's low-income populations and migrant workers. Research into the transformation of streets in these areas can reveal how improvements in infrastructure and living environment quality can foster social integration and stimulate economic activities. Moreover, such studies can help deconstruct the social inequalities and spatial segregation inherent in urban development, proposing fairer and more inclusive urban planning strategies.

The representative and exemplary role of UVs

UVs, as typical representatives of informal settlements, reflect the complex relationship between urban and rural areas due to their unique geographical and social structures. Research into the transformation of streets in UVs can provide insights into addressing internal urban development imbalances and exploring how existing social and physical structures can be utilized to enhance urban space efficiency. For example, by promoting the integration of commercial activities and neighborhood services through street transformation, replicable models can be provided for other high-density, single-function residential areas in the city, thereby facilitating a more dynamic and mutually beneficial urban spatial arrangement.

Enhancing social inclusivity and cultural diversity

Systematic transformation and research of streets in informal settlements are crucial for understanding and promoting social inclusivity and cultural diversity. Street transformation projects can be designed as platforms for neighborhood participation and cultural expression to encourage interaction both within and outside the neighborhood. This not only helps enhance residents' sense of identity and belonging to their neighborhood but also facilitates cultural display and exchange, reducing social barriers within the city and fostering understanding and respect among different social groups.

7.2.2 Qualitative and quantitative measurement of UV streets

This dissertation explores the multifaceted identity and role mechanisms of streets from both qualitative and quantitative perspectives. By synergizing qualitative and quantitative methods, it successfully establishes a comprehensive theoretical and empirical framework, overcoming the limitations of using a single approach in studying street spaces.

In the qualitative analysis, the research thoroughly elucidates the dual identity of streets as both transportation networks and social spaces. This analysis clarifies the complex role of streets as transportation infrastructure and public spaces, emphasizing the necessity and challenges of balancing transportation and social functions within limited urban spaces.

The qualitative themes of livability and mobility provide a foundation for the quantitative analysis of residents' mental health and travel behavior. In studying mobility, we opted for drone sampling and multi-object tracking due to the unique distribution of UVs, allowing for an in-depth investigation of individual urban functional areas rather than proposing generalized solutions for all urban spaces. By integrating nonlinear regression models, this approach reveals the correlation between street physical environments, facility configurations, and street mobility.

In mental research, to avoid the limitations of traditional surveys, such as small sample sizes, lack of representativeness, and laborious data collection processes, we used social media data alongside NLP and deep learning techniques to validate and expand upon the qualitative assumptions about street livability and residents' mental well-being. Comparative studies with FSs further confirm the pivotal role of streets in UVs in promoting residents' mental health.

Overall, quantitative research provides practical guidance on finding the optimal balance between transportation accessibility and street mobility, helping urban planners identify key priorities and influential factors.

7.2.3 Establishing comprehensive indicators for quantifying macro and micro street environments

In developing a comprehensive set of quantitative indices for street environments at macro and micro levels, this thesis has established an innovative framework that integrates crucial variables from both dimensions to provide a scientific basis for assessing urban streets. The macro-level indicators encompass the street network, public transportation, building density, and land-use intensity and type. At the micro level, through streetscape perception, a series of visual elements and human-scale indices related to street vitality have been extracted, such as the Green Index, Enclosure, Walkability, and Imageability. These metrics are calculated using semantic segmentation and deep learning methods on streetscape imagery, effectively quantifying the influence of various visual elements on pedestrian experience.

The novelty of this comprehensive index system is evident in two main aspects: first, the use of diverse data sources presents the multidimensional attributes of the street environment on a more granular scale, enabling a thorough understanding of both the overall and detailed characteristics of urban streets. Second, correlating indices across different scales provides a panoramic view of the street environment while revealing the distinct contributions of macro and micro factors in facilitating UV street transformation. At the macro level, the study proposes reducing industrial area density surrounding UVs and prioritizing public transportation while limiting automobile access to residential zones. Furthermore, maintaining low street density in marginalized areas can encourage e-commerce, thereby alleviating stigmatization and improving mental health. On the micro level, the study found that wider streets attract more pedestrians, leading to higher mobility. Moderate building density and reasonable building proportions effectively support pedestrian activities. When buildings comprise 55-65% of the total visual proportion, the street environment offers an excellent pedestrian experience. However, overly dense or sparse building layouts weaken street appeal and reduce pedestrian traffic.

Establishing this macro-micro spatial index system enables a comprehensive understanding of the research object. This framework can also be adapted to other urban areas, such as public spaces or parks, providing a robust theoretical framework for enhancing the sustainability of urban spaces.

7.2.4 Combing objective and subjective perspectives to comprehensively assess UV streets

In the assessment of UV streets, employing a combination of subjective and objective assessments is particularly meaningful. Objective assessment relies on technology and data, such as drone aerial photography, on-site measurements, and online map data, which can quantify the physical and functional characteristics of UV streets. With this objective data, researchers can gain a detailed understanding of the street layout, width, number of floors, and other attributes, providing a scientific basis for the transformation and planning of UVs. This information helps to reveal the functional distribution of streets, such as the scope of commercial areas and the layout of residential areas, as well as how the streets affect the daily activities and neighborhood dynamics of residents.

Simultaneously, the subjective assessment of UV streets focuses on residents' perceptions and experiences, as residents' perceptions of street space impact their quality of life and mental health. Through the analysis of social media data, SVI, and resident surveys, researchers can obtain direct feedback from residents on the street environment, such as their feelings about street safety, cleanliness, or greening. This subjective assessment aids in understanding how residents interact with these street spaces and how these interactions, in turn, affect their sentiments and behavioral patterns.

By integrating these two methods of assessment, a more comprehensive perspective can be provided for the improvement of UV streets. It ensures that street designs not only meet technical and functional needs but also align with residents' mental and emotional needs. This integrated assessment method emphasizes the importance of human-centered design, promoting the formulation of UV street renovation strategies that are more inclusive and sustainable, ultimately enhancing the quality of life and neighborhood well-being of UV residents.

7.2.5 Evaluating methodological innovations in street quantification: Benifits and critiques

This study's uniqueness on a methodological level involves not only the integration of existing technological approaches but also reevaluates the positioning and value judgement between multi-source data and urban research paradigms. The core innovations can be summarized in four main aspects, although a critical examination of their limitations is equally essential.

Firstly, the "hybridization" of multi-source data and the dynamic depiction of urban scenarios offer new thought processes for the planning studies of UVs. Traditional "linear" or single-source data analysis often falls short in effectively presenting rich urban details. Here, the coupling of diverse data sources like drone imagery, street view photographs, and social media texts indeed enhances the immediacy and multifaceted nature of spatial quantification. However, this "hybridization" also introduces algorithmic complexity, making it difficult to provide clear explanations for intricate mechanisms and local anomalies, thus creating a potential "black box" in analysis and modeling. Additionally, significant accuracy disparities between different data sources can lead to inconsistencies or selective biases when adapting across platforms, such as issues with unit standardization. Pursuing data diversification without ensuring interpretability and stability might undermine the reliability of research findings.

Secondly, the progressive integration of research scales showcases a systemic thought process from macro to micro, organically linking factors like space, behavior, environment, and psychology. However, without adequate theoretical support in spatial disciplines, cross-scale inferences might lead to contradictions between localized conclusions and overall perceptions, or cause information gaps due to weak logical connections. For example, quantifying urban village street spaces based on a 5D theory on a macro level and measuring pedestrian traffic based on Jan Gehl's pedestrian behavior theory might yield discrepancies. Especially under unique built environments and complex socio-cultural contexts, piecing together indicators from different theories could overlook underlying spatial and sociological differences. If the methodological design fails to clarify the applicability and priority of each analytical layer, overly stacking macro and micro factors might lead to theoretical disconnection and operational confusion.

Thirdly, although the integration of objective and subjective assessment methods enhances the humanistic depth of the study, it also entails inherent conflicts: quantitative indices emphasize uniformity and repeatability, while subjective perceptions often vary significantly due to cultural, experiential, or psychological factors. When these two outcomes conflict, deciding which perspective to prioritize often lacks an objective criterion. Overlooking social inequalities or cultural biases in the collection and interpretation of subjective data could render the research one-sided, potentially reinforcing existing misunderstandings and biases. Over-reliance on technological tools to attain so-called "objective truth" might reduce the richness of human contexts to mere quantifiable indicators, losing qualitative depth.

Lastly, the intersection of machine learning and spatial planning indeed shows the cutting-edge advantages of data mining and algorithm learning, but it also accentuates potential issues like model bias and unbalanced training samples within the urban domain. Solely pursuing technical efficiency and precision without thoroughly questioning the underlying values or decision-making bodies could exclude minority or non-mainstream groups from analysis and planning decisions. Certain variables, which may rank lower in importance, often play a crucial role in urban village streets, such as street greening. Such unconscious objective biases might result in gaps in street space planning.

In conclusion, while this study demonstrates innovative approaches through multi-source coupling, multi-scale integration, and human-machine interaction, it inevitably faces unavoidable technical and social dilemmas: balancing between complex data and models, opposing multi-dimensional scales and socio-cultural contexts, and the tug-of-war between technological objectivity and subjective experiences. Only by maintaining a sustained and robust critique of these potential limitations can we avoid turning innovative quantitative methods into mere symbols of instrumentalism and truly serve street renewal with multi-source data and comprehensive methodologies.

7.3 Methodological implications for follow up research

7.3.1 Application and challenges of SVI data in evaluating environmental perceptions

In this study, SVI data were employed to meticulously extract 150 types of street elements through semantic segmentation techniques, and a mathematical model was used to objectively assess residents' perceptions of urban street environments. Our methodology showcases two primary academic advantages: first, leveraging large-scale street view data collection, this study covers a broad geographic range, effectively addressing the challenges of assessing street perception in complex urban environments (Anthopoulos and Kazantzi, 2022). Moreover, by integrating data from various street view elements, the research comprehensively evaluates how these factors influence residents' environmental perception, addressing limitations in previous studies that were constrained to a few street elements (Chung et al., 2022; Elsadek et al., 2019).

SVI represents an innovative form of geographic data, offering a 360-degree panoramic view for real-time observation from the pedestrian perspective, encompassing both natural and artificial landscapes. This technology not only enhances the accuracy of street environment perception assessments but also promotes a more human-centered and adaptive urban environment design. However, several challenges arise when utilizing SVI data: data access is hindered by multiple constraints such as user permissions, image quality, uneven spatial distribution, and temporal instability. Most SVI data are sourced from commercial services like Google or Baidu, and the business policies and pricing models of these companies restrict the availability and cost-effectiveness of the data. Furthermore, image collection is affected by political, economic, and technical factors. In particular, GSV services are not comprehensively covered in regions like Africa, South America, and the Middle East. Image quality varies due to lighting, weather conditions, and scene occlusion, while inconsistencies in time labels and update frequencies complicate research, limiting the applicability of SVI data in comprehensive urban environment and time-sensitive studies.

Future SVI data-driven research on environmental and perception assessment could seek breakthroughs in the following ways: (1) developing crowd-sourced street view platforms such as OpenStreetCam and Mapillary to resolve issues of spatial coverage and temporal sampling frequency; (2) integrating multiple data sources, such as remote sensing imagery and geotagged social media data, to conduct multi-perspective, multi-layered urban environmental studies through deep learning and big data analytics; (3) accelerating real-time SVI data uploads using 5G technology and enhancing data diversity and availability through cloud storage; and (4) combining urban 3D models, such as Surface Elevation Model (SEM) or Light Detection and Ranging (LiDAR), with model databases to rapidly generate virtual cities with specific features, thus improving the reliability and accuracy of assessments.

7.3.2 Application of drones in street and pedestrian research

Drones offer advantages in capturing and analyzing street vitality and the built environment, providing important insights for subsequent research. With their comprehensive aerial perspective, drones can efficiently gather high-quality, wide-angle images and videos, revealing the spatial patterns of street networks, pedestrian traffic, and public space layouts. These high-resolution aerial images enable researchers to capture details closely tied to street vitality, such as pedestrian mobility, street furniture, landscaping, and more.

The flexible data collection capabilities of drones can adapt to different research needs, providing a variety of perspectives. For example, in UVs and other high-density informal settlements, drones can capture street scenes at a micro-scale from specific flight altitudes, revealing the intricate interactions between pedestrians and the physical environment. Due to time and resource limitations, this innovative methodology has not been fully validated and cross-checked. Future research can cross-verify pedestrian flow estimates by combining traditional pedestrian counting methods or counting pedestrians in SVIs taken simultaneously to ensure completeness and accuracy.

Additionally, drones integrated with advanced CV and artificial intelligence technologies, such as YOLO and DeepLab models, can efficiently detect, track, and analyze multiple targets in aerial videos. With the introduction of deep learning models, researchers can improve the accuracy of drone data, providing a more scientific basis for evaluating street and pedestrian behavior. Developing more pedestrian-related datasets is crucial, such as those identifying age groups and behaviors. Current pedestrian datasets are primarily based on a horizontal perspective, making it difficult to identify pedestrians' age and other attributes from a top-down view. Drones can address this limitation. Furthermore, through drones and deep learning models, behaviors such as sitting and conversing can be identified, offering more detailed insights into street vitality. This dissertation reaffirms that streets are vital locations for residents, but details like activity types, dwell time, and emotional responses require further investigation to reveal the dynamic patterns of public space activities and their connection to resident well-being. Drone data, combined with information on time, location, and frequency, helps analyze public space usage patterns, providing data support for urban planning. Future research should explore how to combine drones with deep learning to finely analyze the diversity and complexity of street activities, deepening our understanding of street vitality and creating public spaces that better meet residents' needs. By identifying and categorizing various activities and behaviors on streets, researchers can gain a more comprehensive understanding of the impact of public spaces on residents' well-being.

However, the extremely fine-grained data captured by drones limits their applicability on a large-scale, city-wide basis, particularly when performing mass, city-wide monitoring. Additionally, drones in aerial operations are subject to external factors such as weather and regulations, posing challenges for future research.

7.3.3 Potential of social media data and NLP techniques in quantifying mental health

Social media data provide a novel quantitative approach to studying residents' mental health. Unlike traditional surveys, social media data can capture genuine emotional expressions in natural environments, free from leading questions or survey context biases. Combined with NLP techniques, social media data can generate objective, repeatable quantitative results and provide large-scale samples at a low cost. This approach helps uncover the complex relationship between residents' sentiments and the built urban environment, compensating for the limitations of traditional surveys in sample size and scope. It offers a new way to better understand urban residents' mental states.

Through multi-level analyses across different scales, social media data can reveal deeper correlations between sentiments and the street environment. By analyzing the spatial distribution and time series of social media data, researchers can explore the potential impacts of specific environmental features on residents' sentiments. Investigating the emotional distribution and behavioral trajectories at various scales, such as neighborhood, street, and regional levels, can highlight residents' emotional responses in different scenarios and their intricate interactions with the built environment. This provides valuable research material for understanding the links between the urban environment and mental health. Future research can further refine the associations between sentiments and the built environment by utilizing data across different spatial scales and time series to reveal the dynamic connections between residents' sentiments and urban surroundings.

NLP techniques offer a wide range of analytical dimensions for quantifying residents' mental health. Sentiment scoring models can quantify different emotional expressions on social media and, by extracting keywords related to behaviors, activities, and age, further categorize social media data to reveal the emotional characteristics of urban residents. By tracking terms related to green spaces, parks, and public spaces in social media comments, researchers can identify these spaces' positive or negative impacts on residents' sentiments and provide valuable insights for urban planning and designing public spaces that better meet residents' needs.

Combining social media data with NLP techniques opens new directions and methods for studying residents' mental health. Future research can improve sentiment scoring models and develop datasets that better align with emotional associations to capture multi-dimensional emotional information, providing more accurate results for understanding the relationship between spatial features of the urban environment and residents' emotional responses. Studies should also focus on identifying the specific effects of different environmental characteristics (e.g., green spaces, commercial areas, and transportation) on sentiments to offer more precise feedback to urban planners and reveal significant correlations between public sentiments and particular elements of the built environment. Ultimately, researchers can investigate the factors influencing residents' mental health by understanding the role of urban spaces and the built environment from different emotional perspectives. This will offer scientific data to support urban renewal, public space design, and enhancements to residents' well-being.

7.3.4 Synergistic use of nonlinear regression models and GWR

Nonlinear regression models have significant advantages in characterizing the relationships between street environments and other variables (including vibrancy), particularly excelling at capturing complex nonlinear relationships. In this dissertation, nonlinear regression models were used to explore the nonlinear relationship between pedestrian flow and the micro street environment, a complex association that traditional linear models struggle to capture adequately. These models help urban planners predict the effects of the street environment on behavior and mobility more accurately, while also identifying threshold effects. When variables exceed specific ranges, their impact on the outcome changes significantly. Additionally, nonlinear regression models are adept at handling the complex interactions between the street environment and other variables, such as the combined influence of street furniture and street form on vibrancy, or the interaction between street width and building density.

Despite the significant advantages of nonlinear regression models in characterizing the relationships between the street environment and other variables, particularly in capturing complex nonlinear relationships and identifying critical thresholds, they have certain limitations. Notably, they lack the geographic resolution to reveal variable relationships and are insufficiently capable of addressing spatial heterogeneity.

In this context, GWR and MGWR can be considered for future research in conjunction with nonlinear regression models. GWR is a spatially-aware model that allows model parameters to vary with geographic location, thus reflecting the relationships between local characteristics and variables more accurately. MGWR further extends GWR by incorporating different spatial scales for each explanatory variable, enabling each to have its own spatial scale parameter in the model. This allows for more precise characterization of the heterogeneity and complex interactions of each variable at different spatial scales. GWR and MGWR can fully capture the spatial variation patterns between the street environment and other variables, providing more detailed spatial scale information and enabling urban planners to develop more targeted planning strategies for different streets and regions. This refined spatial resolution is especially suitable for assessing the impact of the street environment on behavior and activities.

Future research could explore combining nonlinear regression models with GWR or MGWR. By integrating the nonlinear models' ability to capture complex relationships with the spatial heterogeneity handling capabilities of GWR/MGWR, researchers can reveal the multidimensional effects of street environments on pedestrian flow, commuting, and activities at the local level. Such combined models can better identify threshold effects and complex interactions among variables, ensuring that planning strategies accommodate both local and overall needs across multiple levels, thus achieving more precise scientific interventions in the design and management of street environments.

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Appendix

A1 Calculation of sDNA

We studied street accessibility based on the spatial syntax (Hillier and Hanson, 1989). We applied sDNA to measure "betweenness", which is a spatial syntactic research tool available as a plug-in for ArcGIS that enables the examination of centrality and network detours (Cooper, 2019). The "betweenness" counts the number of geodesic paths that pass through a vertex, i.e., the number of times the vertex lies on the shortest path between other pairs of vertices. It has the potential to forecast the most accessible streets in the area (Al_Sayed et al., 2014). Additionally, the "radius" refers to the metric distance from each segment along all of the available streets and roads from that segment up to the radius distance. As our empirical study aims to measure the daily accessed streets, we use 400 m as the shortest radius based on previous definition of the walking radius to measure the street walking potential in the selected area (Al_Sayed et al., 2014). The specific calculation is shown below.

$$\textbf{Betweenness}_{(x)} = \sum_{y \in N} \sum_{z \in R_y} W_{(y)} W_{(z)} P_{(z)} OD_{(y,z,x)}$$

$$\boldsymbol{OD}_{(y,z,x)} = \begin{cases} 1, & \text{if } x \text{ is on the } f \\ 1/2, & \text{if } x = y \neq z \\ 1/2, & \text{if } x = z \neq y \\ 1/3, & \text{if } x = y = z \\ 0, & \text{otherwise} \end{cases}$$

In the formula, $W_{(y)}$ is weight of a polyline y and $W_{(z)}$ is weight of a polyline z; $P_{(z)}$ is the proportion of any polyline z within the radius. OD represents the origin destination, in which built environment variables were categorized into quartiles and modeled. The geodesic endpoints are y and z, not x where the betweenness is being measured. The contribution of 1/2 to $OD_{(y,z,x)}$ reflects the end links of geodesics, which are traversed half as often on average, as journeys begin and end in the link center on average. The contributions of 1/3 represent the origin of self-betweenness.

A2 Sample and evaluation mechanism of sentiment analysis

To evaluate the effectiveness of the model in text sentiment analysis, we use precision, recall, and F_1 score, as per the official evaluation system of EVALITA 2016. Since it is necessary to indicate the F_1 score both for class 0 and class 1 and in order to avoid an unclear notation, the 0 and 1 subscripts will be

Table A2.1: Examples of emotional polarity labeling regarding settlements.

Text	**Categories**
The trees in the neighborhood are super healing!	1
Living in a sunless UV, struggling desperately to make ends meet in Shenzhen, a first-tier city.	0

used for this purpose, assuming that the F_1 score will continue to be used, both in the case of F_0 notation (not to be confused with F_0 score) and in the case of F_1 notation. In detail:

$$P_c^p = \frac{\text{correct }_c^p}{\text{assigned }_c^p}$$

$$R_c^p = \frac{\text{correct}_c^p}{\text{total}_c^p}$$

$$F_c^p = 2\frac{P_c^p R_c^p}{P_c^p + R_c^p}$$

where p indicates the polarity, both positive (it will be indicated as pos) and negative (it will be indicated as neg), while c stands for the considered class (0 or 1). Moreover, the F_1 score for each task is computed as the average of the F_1 scores of the respective pair of classes:

$$F^p = \frac{F_0^p + F_1^p}{2}$$

Finally, the overall F_1 score is given by the average of the F_1 scores relative to the two polarities:

$$F = \frac{F^{pos} + F^{neg}}{2}$$

A3 The attention mechanism of NLP

The attention mechanism enables the model to focus on relevant parts of an input sequence when the sequence is too long for a typical NLP model. In our study, the attention mechanism helps determine the relevant weights of each word token in the input of Weibo posts and generates corresponding hidden states during training to best characterize Weibo sentiment. The attentional mechanism formula is as follows, where Q, K, and V are three vectors, query, key and value, created based on input embedding, and dk is the dimension of key vectors.

$$\text{Attention }(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V$$

For the purposes of this article, only the negative and positive tags will be considered, assuming a value of 0 or 1 respectively in the absence or presence of the corresponding sentiment. Therefore, the task at hand is to detect the presence of positive emotions. If positive emotions are detected, the output positive may be assigned to category 1; otherwise, it is assigned to category 0. Examples and the evaluation process of the effectiveness are in the supplementary materials.

A4 Supplementary materials for Paper III

Table A4.2: The adjacency matrix of the variables influencing PSI.

Variables	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**
A1	0	0	0	0	1	1	0	1	0	‘	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	1
A3	0	0	0	0	1	1	0	0	0	0	0	0
A4	0	0	0	0	1	1	0	0	0	0	0	0
A5	0	1	0	0	0	1	0	0	0	0	0	1
A6	0	0	0	0	0	0	0	0	0	0	0	1
A7	0	0	0	0	0	0	0	0	0	1	0	0
A8	0	0	0	0	1	0	0	0	0	0	0	0
A9	0	0	0	0	0	0	0	0	0	1	0	0
A10	0	0	0	0	1	0	0	0	0	0	0	0
A11	0	0	0	0	1	1	0	0	0	0	0	0
A12	0	0	0	0	00	0	0	0	0	0	0	0

Table A4.3: The reachable matrix of the variables influencing PSI.

Variables	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**
A1	0	0	0	0	1	1	0	1	0	‘	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	1
A3	0	0	0	0	1	1	0	0	0	0	0	0
A4	0	0	0	0	1	1	0	0	0	0	0	0
A5	0	1	0	0	0	1	0	0	0	0	0	1
A6	0	0	0	0	0	0	0	0	0	0	0	1
A7	0	0	0	0	0	0	0	0	0	1	0	0
A8	0	0	0	0	1	0	0	0	0	0	0	0
A9	0	0	0	0	0	0	0	0	0	1	0	0
A10	0	0	0	0	1	0	0	0	0	0	0	0
A11	0	0	0	0	1	1	0	0	0	0	0	0
A12	0	0	0	0	00	0	0	0	0	0	0	0

Table A4.4: The intersection between reachable and antecedent sets.

Variables	**The reachable set**	**The intersection set**
A1	A1, A2, A5, A6, A8, A10, A12	A1
A2	A2, A12	A2
A3	A2, A3, A5, A6, A12	A3
A4	A2, A4, A5, A6, A12	A4
A5	A2, A5, A6, A12	A5
A6	A6, A12	A6
A7	A2, A5, A6, A7, A10, A12	A7
A8	A2, A5, A6, A8, A12	A8
A9	A2, A5, A6, A9, A10, A12	A9
A10	A2, A5, A6, A10, A12	A10
A11	A2, A5, A6, A11, A12	A11
A12	A12	A12

Table A4.5: Discretization of influencing variable ranges for PSI assessment.

	Probability (%)									
Variables	a		b		c		d		e	
	FS	UV	FS	UV	FS	UV	FS	UV	FS	UV
Transport-ation	0–0.15	0–0.159	0.15–0.27	0.159–0.313	0.27–0.421	0.313–0.479	0.421–0.614	0.479–0.692	0.614–1	0.692–1
Street	0–0.248	0–0.216	0.248–0.374	0.216–0.355	0.374–0.501	0.355–0.493	0.501–0.688	0.493–0.651	0.688–1	0.651–1
Bus route	0–0.156	0–0.139	0.156–0.291	0.139–0.276	0.291–0.444	0.276–0.428	0.444–0.641	0.428–0.61	0.641–1	0.61–1
Metro station	0–0.159	0–0.102	0.159–0.322	0.102–0.276	0.322–0.488	0.276–0.447	0.488–0.693	0.447–0.668	0.693–1	0.668–1
Metro route	0–0.102	0–0.103	0.102–0.226	0.103–0.276	0.226–0.373	0.276–0.455	0.373–0.602	0.455–0.663 0.602–1	0.663–1	
Public	0–0.127	0–0.139	0.127–0.245	0.139–0.286	0.245–0.399	0.286–0.453	0.399–0.61	0.453–0.66	0.61–1	0.66–1
Automobile accessibility	0–0.254	0–0.265	0.254–0.443	0.265–0.432	0.443–0.586	0.432–0.583	0.586–0.763	0.583–0.765	0.763–1	0.765–1
Industrial	0–0.186		0.186–0.343		0.343–0.507		0.507–0.688		0.688–1	
Residential	0–0.127	0–0.111	0.127–0.253	0.111–0.251	0.253–0.415	0.251–0.43	0.415–0.622	0.43–0.636	0.622–1	0.636–1
Commercial	0–0.147	0–0.117	0.147–0.279	0.117–0.25	0.279–0.439	0.25–0.404	0.439–0.649	0.404–0.593	0.649–1	0.593–1
Walk accessibility	0–0.219	0–0.248	0.219–0.391	0.248–0.417	0.391–0.555	0.417–0.575	0.555–0.729	0.575–0.763	0.729–1	0.763–1
PSI	0–0.515	0–0.556	0.515–1	0.556–1						