PAPER

Computational Urban Design: An Exploration in the Context of New Urban Science

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Abstract: **Classic urban design theories and research methods have been limited to qualitative approaches, such as subjective intuition and small-scale surveys. With the emergence of new urban science, adopting big data, virtual reality (VR), and wearable sensors, it is possible to achieve a precise analysis of people's perceptions and behaviors in urban spaces. In this way, not only will new insights in urban studies be inspired but also high-quality, human-scale space design can be generated. This study constructs a systematic and computational urban design system that covers the three aspects of technical applications, data-informed, evidence-based, and algorithm-driven urban design. First, the data-informed urban design helps identify problems and formulate strategies. Multi-source city data, such as Point of Interest (PoIs) data and AutoNavi map path planning API, help to identify the needs, functions, and characteristics of the citizens. The evidence-based urban design with specific inquiries helps to select the design intervention point and control spatial elements. VR technology, wearable biosensors, and the visualization SP method are combined to measure space utility. The final algorithm-driven part can use sDNA, UNA, and visualizer to summarize the types of urban spaces, perform morphological analysis and vitality evaluation, and further adjust the design. It can be seen that the application of this framework can make the entire design process more automatic, efficient, and robust under the existing constraints. In addition, it helps the perspective of urban design expanding from the previous "top-down" perspective to the "bottom-up" perspective, transforming from a two-dimensional to a three-dimensional, obtaining real-time feedback and optimizing design accordingly, emphasizing human perception and human-oriented scale.**

1. INTRODUCTION

1.1. THE DESIGN-ORIENTED ANALYSIS AND HUMAN-ORIENTED THINKING IN URBAN DESIGN

Urban design is essentially a process of shaping urban morphology and creating high-quality urban spaces by predicting public needs.[1] Therefore, studies on urban morphology and research on citizens' perceptions and behaviors have always been the two essential aspects of urban design. Since the 1960s, classic theories have mostly conducted qualitative research and theoretical discussions on this process, developing a series of analytic methodologies based on subjective experience and manual procedures. Therefore, the development of the fundamental urban design analysis has always been the core of its research and practice. With the urbanization process transforming from high-speed contribution to high-quality renovation, more comprehensive urban design elements, such as function, economy, emotion, and environment, should be considered.[2] People's perspectives are gradually changing from "what the city looks like" to "what we feel in the city."[3]

Although scientific measurements and human-centered designs have become increasingly important in recent years,[4] traditional design practitioners still find it difficult to deal with complex urban data, not to mention intricate emotions. First, manual analysis and empirical assessment are incapable of identifying urban features when multiple morphological elements, such as architecture, street, and district, overlay each other. Second, when it comes to measuring human perception and behavior, the results mostly rely on either on-site behavior annotation or small-scale questionnaires. Consequently, this method is rarely applicable in design practice because of its lack of efficiency and susceptibility to accidental factors. Third, the quality of the current urban design mainly depends on the designers' subjective experiences, which have obvious disadvantages in spatial and temporal dimensions. Consequently, urban design is often guided by heuristics, rule of thumb, and a lack of examination of the outcomes of their habitual use. Therefore, the rising demand for new research directions is clear. Success in this endeavor requires human-oriented thinking and design-oriented analytical techniques. In this context, urban design urgently needs the support of multi-source data to examine society and provide an accurate analysis by observing human emotions.

1.2. THE EMERGENCE OF NEW URBAN SCIENCE FOR URBAN DESIGN

The issues mentioned above can be addressed by new urban science, which relies on computational algorithms and multi-source urban data. Using quantitative analysis and calculation methods to assist urban design, new urban science has promoted unthinkable possibilities in recent years.[5] Numerous research territories are booming and urban design is witnessing a paradigm shift from being expert-dominated to being human-oriented.[6] Prior to new urban science, classic design theories and research methods were limited to subjective intuition and small-scale surveys. However, these obstacles have been overcome by a new infrastructure for data collection, quantitative analysis, and crowdsensing.[7]

Thomas Kvan states that "The future of urban design is implicitly connected with datasets."[8] An increasing number of scholars also argue that only embracing urban data analysis as the input for urban design can facilitate better urban design strategies and understandings.[9] Nowadays, through the adoption of big data, virtual reality (VR), and wearable sensors, it is possible to achieve a precise analysis of people's interactions and perceptions of urban space. In this way, not only will new insights in urban studies be inspired but also high-quality, human-scale space design can be generated. With the integration of a computational algorithm and experiencing decisions, rapid design prototyping is capable of testing countless designs and optimizing their performances.[10] Innovations in analytical techniques, such as geometric and geographic analysis of urban morphology, can also provide a unique way to qualify the effects of urban design. Improvements in all-new urban science would convert urban design into a better place-making approach.

2. LITERATURE REVIEW

2.1. COMPUTATIONAL URBAN DESIGN

A systematic review was conducted to map the emerging literature in related fields. With the keywords "urban design," "big data," and "new urban science," more than 200 representative journal articles published on the Web of Science in recent years were selected as the dataset. Their connections were visualized via Bibliometrix, a freely available application for visualizing and analyzing trends and patterns in scientific literature. Consequently, three new research directions have emerged on the leading edge of the literature (Figure 1). A clear conceptual framework and sophisticated empirical study can help to illustrate the emerging research potential of the new data environment and analytical methods.

In this context, a systemic brand-new framework for computational urban design can be proposed, which integrates big data, machine learning algorithms, and geographic design to achieve

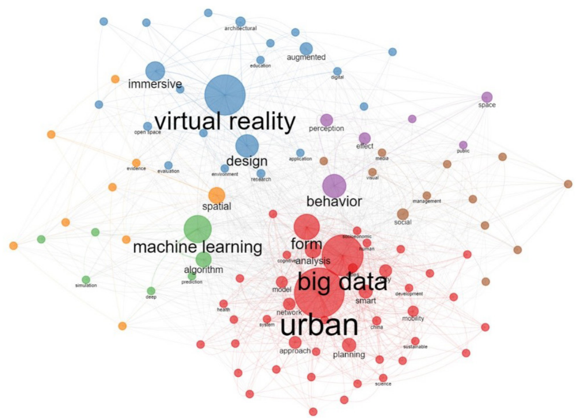


Figure 1. Mapping recently published literatures via Bibliometrix.

a refined analysis from a human-oriented perspective. At the same time, quantitative assessment of non-entity elements, such as quality and vitality, is carried out from both top-down and human-scale perspectives. Multidisciplinary knowledge is integrated to better assist urban design. Apart from parametric design focusing on "find" and "generation" design by the algorithm, the key point of computational urban design is to take advantage of integrating new urban data, technology, and algorithms into the whole process of urban design while paying attention to the integration of scientific analyses and design approaches. Computational urban design, an exploration framework for complex urban design projects, can automatically fulfil formalizable design requirements.[11] It contributes to understanding the coherence of tangible and intangible building environments better, bringing new possibilities to the aspects of urban design in site analysis and project assessment.

2.2. DATA-INFORMED METHOD

Assessment of large-scale subjective perception and measurement of objective spatial morphological impacts are the emphasis of a data-informed urban design study. On the one hand, professionals can rapidly grasp people's cognition and emotion of spatial features based on multi-sourced data that describe their feelings.[12] On the other hand, human-scale spatial characteristics may be retrieved from street view images (SVIs) using machine learning algorithms.[13] In addition, this procedure is more feasible using ArcGIS and urban spatial analysis tools such as place syntax, urban network analysis (UNA), spatial design network analysis (sDNA), and form syntax.[14] By combining urban functional facility data with demographic data that characterize service levels, it is possible to estimate the citizenry's demands and measure the socio-economic effects of the spatial form.[15] When these studies are paired with mobile location service data (GPS, LBS data, Weibo sign-in data, etc.) that show people's travel patterns, non-physical factors such as quality and vitality may be addressed more precisely.[16]

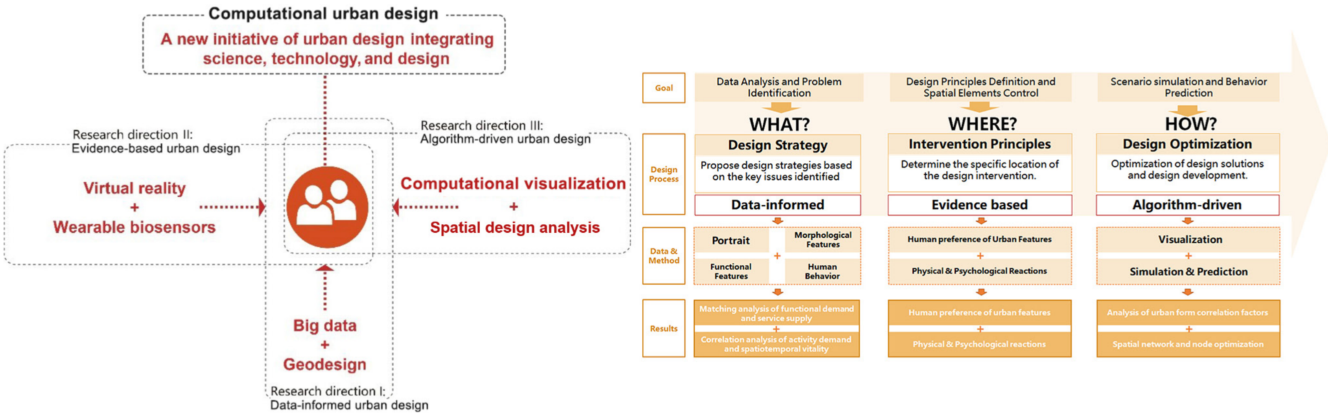


Figure 2. Analytical framework (left) and the application of computational urban design in practice(right).

2.3. EVIDENCE-BASED METHOD

The purpose of evidence-based computational urban design is to use immersive VR to provide an individual perception verification method for more accurate and efficient control of design components. When eye-tracking, heart rate variability (HR), electrocardiogram (ECG), and electrodermal activity (EDA) are combined with VR, users can get an immersive experience, thus, testing the human body's physiological reaction and psychological responses in diverse places and analyzing improved indications to help guide the placement of the optimal design.[17]

2.4. ALGORITHM-DRIVEN METHOD

The focus of algorithm-driven urban design lies in the development of design tools through computer technologies such as visualization and machine learning algorithms, which mainly include the following three categories: First, an ArcGIS-based visualization tool that combines geographical morphological components at various scales and further links economic and social attribute data. Such tools can help designers analyze sites,[18] summarize the types of urban spaces,[19] and further generate urban design projects. Second, a design creation tool based on the generative adversarial network (GAN) algorithm, which has emerged as one of the most promising unsupervised learning approaches in recent years. GAN can efficiently realize feature learning and regeneration owing to the collision of two deep neural networks, which is ideal for the demands of planning design.[20] This type of tool may produce a plan based on the designer's specifications or existing urban prototypes, displaying more space possibilities.[21] The last one focuses on program evaluation, which may simulate and forecast behavior patterns before and after the program is completed, such as walking paths, traffic flow, and travel time.[22]

3. RESEARCH FRAMEWORK

3.1. ANALYTICAL FRAMEWORK

This study proposed a computational urban design system supported by new data and tools. The new algorithm is applied to the core of the entire urban design process, with an emphasis on fusing science, technology, and design depth, in the form of quantitative calculation to support a better design.

To deal with complex urban design projects, computational urban design must involve three major directions: data-informed, evidence-based, and algorithm-driven (Figure 2 left). The purpose of the data-informed direction is to identify the problems of the base, guide the main design strategy, and clarify the direction of the urban design intervention. The evidence-based urban design aims to locate the specific space that has to be renovated and to identify how to start the design based on human perception. The algorithm-driven urban design is meant to improve the outcome of urban renewal, offering optimization strategies through simulation and prediction. This study further explains this system by using practical cases.

3.2. METHODOLOGY

Strategy: Data-informed. Multi-sourced urban data, including LBS, PoIs, and social media data, provide various approaches to deepen urbanists' comprehension of urban forms and spatiotemporal layouts.[23] Furthermore, geodesign was recently incorporated into the urban environment domain and developed into a digital analysis platform,[24] which can tightly link it to urban design through informed simulations.[25] Designers can be well informed by these information tools and, then, seek an optimal strategy for spatial challenges. Overall, it helps with functional guidance and spatial problem identifications from a macro to a micro-scale. Alougth the sensitivity of these analyses to sample selection and spatial unit scale cannot be ignored, the rapid techniques' advances such as multi-scale geographic models, and machine learning-based non-linear methods, are attempting to solve these above issues and provide more refined guidance in urban design (Figure 2 right).

Design: Evidence-based. Recently, the development of VR head-mounted displays has further promoted communication among space users and designers. The aforementioned biometric

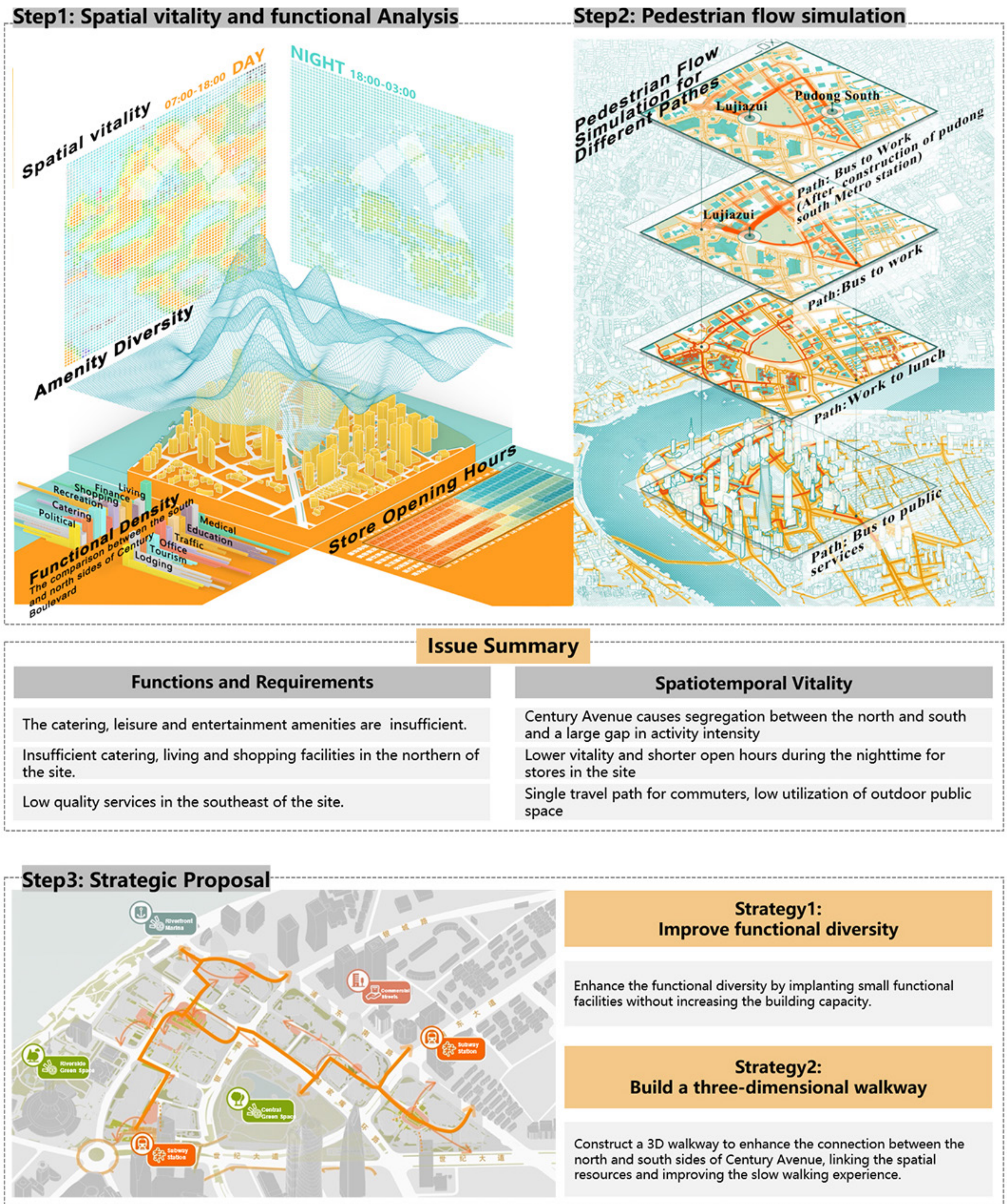
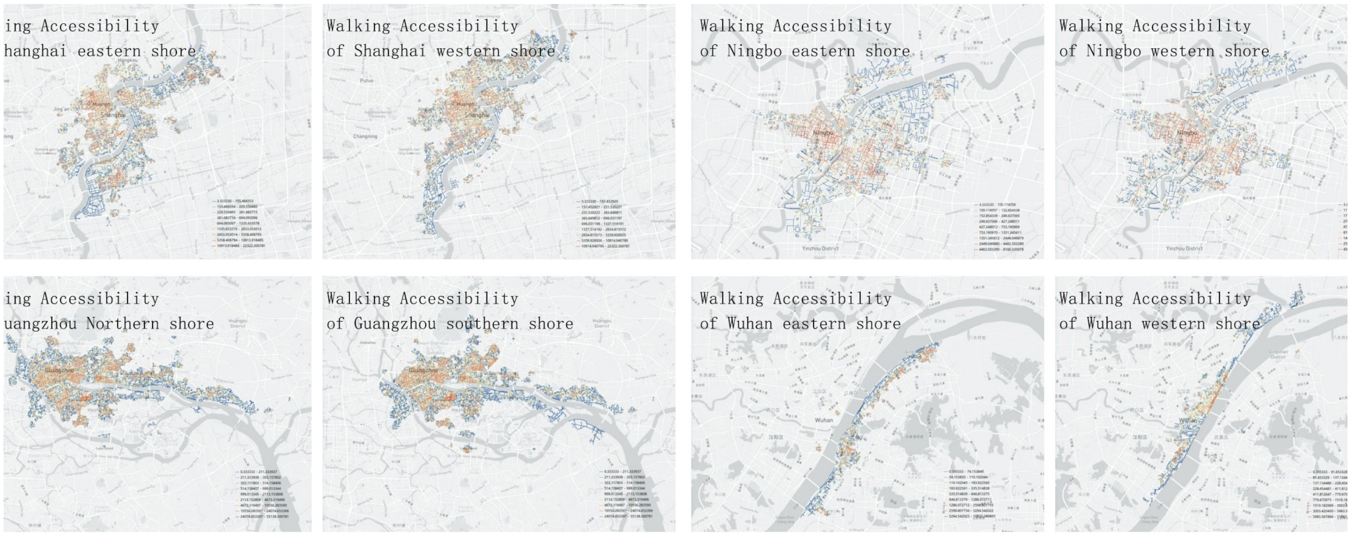
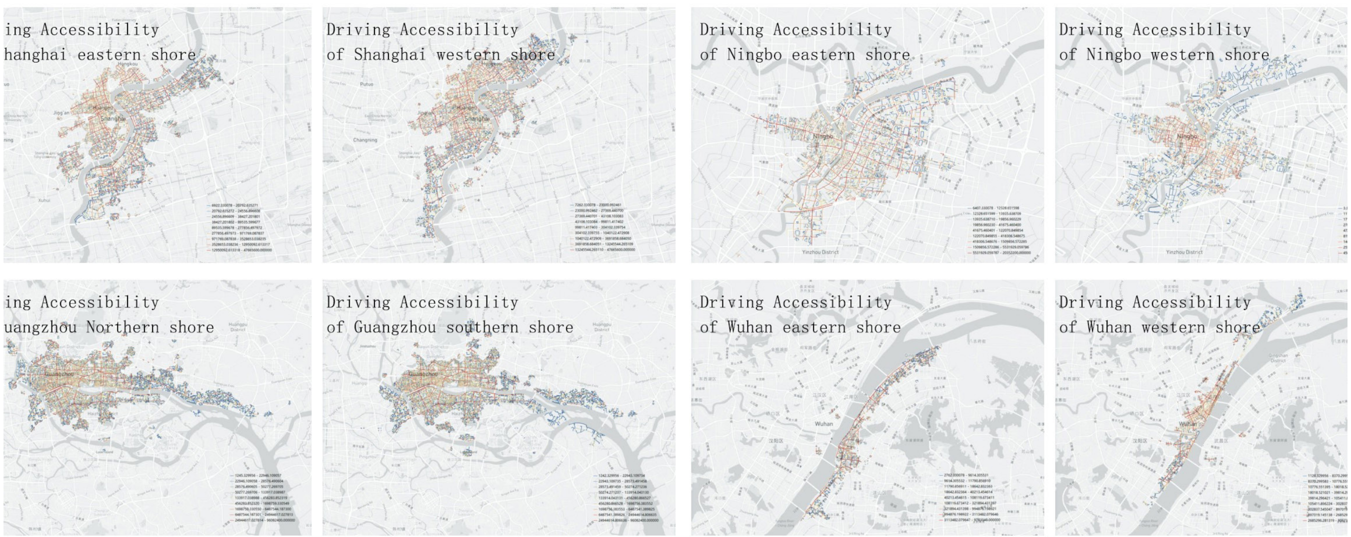


Figure 3. The Map of Vitality and Amenity Density (Left)+Simulation of Path Planning API (Right) and the Strategy of Connecting Century Avenue.



a) Accessibility of pedestrian network



b) Accessibility of vehicle network

Figure 4. The spatial design prototyping, Recording Movement, Affective States and Mapping Intervention Points via Wearable Biosensors.

data allow researchers to measure the impact of various spatial features of human perceptions that are difficult to collect directly.[26] Therefore, VR, combined with biosensors, can help practitioners diagnose urban spaces and improve them by controlling unmanageable design elements and using data that is considered "unmeasurable." Although those methods are now mainly confined to the laboratory with the abstract expression of the real scene, the conclusion is often too ideal.[27] The reliability of the measurements still needs to be improved, as the results are heavily dependent on the performance of the sensing equipment. Nonetheless, objective measurements of individual perception are more conducive to revealing the 'hidden' qualities of space than traditional methods such as self-reported questionnaires. Only when the applicable evidence-based tools are available to designers, the "hidden" quality that influences human behavior can be fully revealed,[28] and the sustainable environment of people-oriented can be truly shaped.

Optimization: Algorithm-driven. A 3D spatial analysis technique is driven by machine learning algorithms and visualization techniques, such as UNA and sDNA, which quantitatively integrate multiple urban spatial morphological elements and social attribute data for analysis. For example, with the help of sDNA and network analysis, we can evaluate the accessibility potential and provide fine-scale optimization at key points. Through rapid feature learning and iteration, computer-aided design based on GAN algorithms can generate site or building layouts based on specific designer requirements or existing urban prototypes. In overall, their use in design has proven to provide planners with a wider range of design possibilities, as well as a greater awareness and control of design concepts.[29]

4. IMPLEMENTATION OF COMPUTATIONAL URBAN DESIGN: A CASE STUDY OF THE SHANGHAI URBAN DESIGN CHALLENGE

In 2020, the Shanghai Urban Design Challenge provided a design objective for a "more globally competitive business district." The design scope covered seven blocks north and east of the Central Greenbelt, which is an enclosed area of approximately 44.9 hectares, from Century Avenue–Lujiazui Ring Road–Dongyuan Road–Binjiang Avenue–Pudong South Road–to Yincheng Middle Road. It aims to explore a land stock update of the business district in terms of business district function, as well as an improvement in its vitality and quality.

4.1. DATA-INFORMED URBAN DESIGN

The data-informed urban design allows us to grasp the spatial characteristics and human needs more accurately. A large-scale and detailed analysis of functional facilities and spatial characteristics is integrated with the real-time analysis of crowd behavior and activities. It helps with functional guidance from a macro perspective and identifies specific spatial problems from a micro perspective. Finally, we can respond to the question of "what should be done in design" by proposing design goals and strategies based on realistic operability and human needs.

POIs data + Baidu Huiyan big data platform: increasing functional diversity to meet various demands of citizens. To ascertain the needs of surrounding citizens, we divided people around the design scope into three categories based on age, education, and income data collected from the Baidu Huiyan platform, provided by the competition organizers. Based on the location based service(LBS) data on collected from the users' mobile phone, this platform can portraying user profilese,by their cell phone type and browsing history, and also record the users' travel behavior. Considering the need for privacy protection, the data is aggretaed on a block or district unit. The results showed that the long-term residents mostly consisted of natives and white-collar workers with high salaries, while the short-term residents were mainly tourists. On the other hand, functional supply was assessed using POIs data from the Gaode map. It was shown that shopping and leisure facilities were insufficient in the northern area, and service levels were rather low in the southern area. Suggestions were made to insert small facilities to increase functional diversity.

Baidu heatmap data + path planning API (Figure 3): connecting open spaces with multi-level pedestrian networks to improve space utilization. To measure urban vitality, we analyzed the distribution of human activities during the day- and night- cycle, based on the Baidu heatmap, a visualization results of kernel density analysis using the location-based service data. It shows the spatial distribution of human social activities' intensity. Subsequently, taking the path planning API of the Gaode map, we simulated commuters' traveling paths when they use the surrounding amenities based on their supply and location. The analysis revealed the following three points. First, commuters mainly took a few express roads rather than branch roads. Second, the connection between the inside and outside pedestrian networks should be strengthened, especially south of Century Avenue. Third, open spaces such as street gardens and public micro-squares are unreachable because of an inconvenient walking network. Under these circumstances, we suggest that a 3D pedestrian system be created, connecting both sides of Century Avenue and public spaces with low accessibility.

4.2 EVIDENCE-BASED URBAN DESIGN

The evidence-based urban design further answers the question of "where the design should be done" and "how to do it" (Figure 4). This leads to selecting the intervention point of the design and the control of the specific spatial elements in the design. The case combines a VR experiment with a visual selection preference method to measure people's preferences for objective spatial elements. The influence of human-scale spatial factors on human physiological perception is further analyzed using wearable physiological sensors. Based on the above two results, a spatial-utility scale can be obtained and, then, used to quantitatively evaluate the space of the site. Subsequently, specific design intervention points and corresponding spatial reconstruction methods can be selected within the site.

VR: Spatial design exploration as creators and users. Designers utilizing a VR system move around the physical space of the room and place virtual building blocks in precise locations. Wireless settings could give participants a chance to experience the space of the 3D modeling environment in a simple way; 171 participants were invited to indicate their preferences among different virtual scenes, to calculate the influence weight of each spatial element based on Nlogit5. The results show that street furniture and façades are the most important elements. Micro-spaces were more attractive, and increasing greening land could significantly improve the quality of public spaces at all scales. Subsequently, design prototypes were provided according to the outcomes.

Wearable biosensors: Urban space diagnosis from a human-oriented perspective The sensors recorded the movement and affective states of a pedestrian while moving through open spaces at our site. The signals collected by wearable biosensors were used to verify and map the human responses to spaces. Designers were, therefore, able to select specific intervention points so that efficient optimization design strategies could be suggested.

4.3 ALGORITHM-DRIVEN URBAN DESIGN

The case illustrates the specific application of algorithm-driven urban design in evaluating a design effect by using sDNA pedestrian flow simulation for a three-dimensional spatial network and

Table 1 Weights for the integrated development in AHP

	Socioeconomic characteristics		Physical space characteristics	
Indicator(x)	Functional mixture	Population density	Accessibility of pedestrian network	Accessibility of vehicle network
Weight(k_x)	0.4033	0.3520	0.1660	0.0787

Table 2 Results of WID

City	Wuhan		Shanghai		Ningbo		Guangzhou	
Waterfront side	East waterfront	West waterfront	East waterfront	West waterfront	East waterfront	West waterfront	East waterfront	West waterfront
Integrated development	0.1467	0.1126	0.6413	0.2657	0.6089	0.6124	0.6297	0.5008
Average score	0.1296		0.4535		0.6107		0.5653	

Figure 5. Analysis of Accessibility After the Network Design and Fine-scale Optimization Design at Key Point.

network analysis to provide fine-scale optimizations, answering the question of "whether the design is done well."

Pedestrian Prediction and Spatial Network Optimization (Figure 5). After construct the 3D network in GIS, pedestrian accessibility was measured based on sDNA. Betweenness centrality among two nodes of 400m and 1200m radius each was selected to reflect the through-movement potential of walking and riding. We measured the accessibility of the spatial network and simulated the pedestrian flow after the completion of the 3d pedestrian system. As shown in figure 5 the flow volumes of main roads and branches around Century Park were significantly increased. Then fine-scale optimizations were conducted at three key points. First, network analysis based on GIS provides the shortest path between two spots. If the path connecting two important spaces made detours, we input elevators and vertical transit to improve the efficiency of the entire network. Second, vertical transportation was divided into three categories according to its accessibility, calculating the carrying abilities of different types of escalators and elevators. If the vertical transportation type cannot support its accessibility, the type should be upgraded to a higher one.

5. CONCLUSION AND LIMITATION

With the emergence of new data and technologies brought by new urban science, computer-aided urban design has become an unstoppable trend. Nowadays, research on computational urban design continues to emerge. However, there is still a lack of a systematic framework to integrate multiple data and technical methods to better support design practices. In this context, it is necessary to further explore architecture with a deep integration of classical design theories and computer algorithms. The progress in this direction is expected to bring the whole-process innovation of workflow to urban design and better support current high-quality urban living needs. This study proposes a set of computational urban design systems that cover three technology application directions: data support, body verification, and algorithm drive. It introduces systematic and scientific thinking into urban design practice, controlling the entire design process and all its directions.

Although the actual design decision-making process faces many uncertain factors, at present, no scheme can be completely divorced from the subjective experience of the designer or subjected to the perception of the local public, government, and developers. However, on the one hand, such a deep learning algorithm of calculation and analytical ability is expected to greatly improve the design from data analysis to support the transformation efficiency. On the other hand, new design tools enable urban research to directly support the central-most part of urban design: scheme generation. More importantly, through simulation prediction, the scheme's effectiveness is evaluated, and the designer and the decision-maker can obtain real-time feedback and check the scheme accordingly. This emphasizes embodied perception and the transformation from a two-dimensional to a three-dimensional and human-oriented scale.

There are still some deficiencies in the computational urban design system. First, the system is based on refined open data and machine learning technology. Therefore, it is still difficult for second-tier and lower cities in developing cities to apply and practice it due to the difficulty of data acquisition and the high cost of computer technology.

This study has some limitations as well. Firstly, although we try to offer a methodological innovation, there are still computational biases and algorithmic biases in reading data as a precise capture of emotions. Secondly, The dataset collected by biosensors, limited by the cost of the experiment, was not filtered from the main population types obtained in the user portrait analysis section. Lastly, in the algorithm-driven aspect, the generative design had not been used in this case study to show its potential and functions.

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