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Smart city in urban design

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A B S T R A C T

This paper surveys the literature on smart cities in urban design. The smart city is the concept of utilizing information communication technology (ICT) in planning, designing, and managing cities. The domain of smart cities ranges from infrastructure, traffic management, public transportation, public health, urban planning, to governance. The benefits of adopting the advanced ICT in the city include the improved efficiency in city operation and management of assets and infrastructure. Transparent governance promotes civic empowerment and participation. Urban designers slowly began to apply smart city tools and research methods in understanding urban spaces despite the benefits. Application of smart city technologies are tested in various areas in urban design; 1) monitoring people's use and activity in public space, 2) documenting the physical settings of public space, 3) finding the optimal urban form with environmental simulation, 4) operationalizing people's perception, and 5) identifying potential space vulnerable for the crime. One of the biggest challenges in introducing smart cities in urban design is the discrepancy between reality and the abstract version of reality from sensors. Since urban design and public space study primarily deals with the quality of place and the social activities in streets, parks, and plazas, validating how the numeric data translates to the quality of environment and user behavior is a necessary next step.

Keywords: urban design; smart city; domains of smart city; information communication technology; literature review

Introduction

As cities deal with complex urban issues, the need to increase efficiency in city operation and management became an interest for scholars. The smart city is an innovative way to solve urban problems as well as other imminent climate issues with innovative technologies. Thus, literature defining the concept of smart city and implementing the idea is growing across the disciplines, including urban planning, information technology, public policy, public health, and other social and computer science.

The definition of the smart city ranges from 1) introducing information communication technology to manage city operation [1, 2], 2) creating a connected network of sensors and infrastructures to improve the efficiency in utilities [1, 3, 4], 3) providing an advanced version of ubiquitous, or always connected, city [5-7], and, 4) proposing governance benefiting from internet-based feedback loops public participation.

Smart city has both positive and negative connotation in urban planning. Pro-smart city planners commend the

new technology can solve imminent social and environmental issues in the city as 19th Century social science research method has sparked modern urban planning [8, 9]. Pro-smart city planners expect digital data and technology can provide insights and evidence to unravel crucial urban issues. Others argue that smart city is just a fad, or 'urban labeling' phenomenon for marketing purposes [10]. They continue that the recent smart cities around the world do not present any evidence in dramatic changes using innovative technology; rather, it expedited 'placelessness' in cities including Songdo (South Korea), Masdar City (UAE), and PlanIT Valley (Portugal) (Greenfield, 2013).

In urban design, scholars have not explored the new technology yet. However, smart city technology and finer-grain data present a more significant potential to decode human behaviors in public space and hidden theories in urban form. Previous studies in urban design primarily focused on the manual observations of human behavior in public space and on the documentation of streets, plazas, and parks in relation to human behavior. These qualitative research methods are effectively identifying the quality of public space and social activities. As a result, few have adopted innovative technology in understanding the city.

Recent studies, however, began to explore smart city technology investigating theories in urban design. Cameras and cell phone GPS devices help monitor users in public spaces. Environmental simulations help optimize building layouts. Computer vision and internet-based surveys operationalize people's perceptions. And cameras, sensors, and computer vision identify the potential urban environment that is vulnerable to crime. This paper will survey the literature on smart cities and the experiments on smart city technology in urban design. We will discuss the needs and the research gap in developing smart city concepts in designing and managing the physical environment.

Survey of Literature on Smart City

As the first step, we will survey the idea, the technology, and the debates in the smart city. The concept of the smart city differs by the academic and professional background of researchers and disciplines. ICT scientists are interested in the application and implementation of ICT in cities. City planners and managers are enthusiastic about improving efficiency in city operation and drafting new policies with the data. In common, the pioneers of smart city agree the potential of smart city technology and data to provide insights and solutions for imminent urban problems.

Definition of Smart City

The notion of smart city converges to the city's management, governance, policy, and planning using advanced information technology. At the same time, scholars diversify the smart city concept based on their professional and research backgrounds. The smart city is a system that is integrated ICT infrastructure and technologies [1, 2]. The system is equipped with multiple dimensions of terminals and embedded devices [1, 3, 4]. In this respect, the smart city is an extended concept of ubiquitous, always connected, city [5-7].

Expanding the use of advanced information technology, the concept of a smart city reinforces governance in a

democratic and heterogeneous society. The increased speed and connectivity allow enhanced citizen participation and responsive feedback [11]. Politicians and policymakers can make informed decisions based on knowledge, creativity, and innovation based on the data collected from various sensors and citizen input [10]. Thus, cities' planning, operation, and management become "instrumented, interconnected, and intelligent city" [12].

Goals and Objectives of Smart City

Despite the wide spectrum in the notion of a smart city, the goals and objectives of a smart city converge towards improving the management and operation of the city. Some information scientists promote the smart city as a testbed for implementing information technology on a large scale [13]. Others extend the goals to improve quality of life by adopting technologies to address people's needs [14-18]. Urban planners stress that the technology and data will help improve the city [10, 19]. The information technology equipped with live-feed data, advanced analysis tools, and an instant feedback loop, powers the decision-makers in city management.

Characteristics of Smart City

Smart city has been characterized as a 3Is ('instrumented, interconnected, and intelligent) system in city operation according to IBM's research and development department. Harrison et al., [12] pointed out the smart city is 'instrumented' because a set of sensors, meters, and appliances constantly collect live data. It is 'interconnected' because a range of services communicates information through a platform. Based on the collected data and the platform, smart city recreates itself based on analytics, modelings, and optimization of the data and the system. The smart city is a system that reorganizes itself to meet people's needs [11]. Compared to 'intelligent city', smart city deals with a higher level of city operation because smart city includes people components in addition to sensors and hardware [20].

Range of Domains in Smart City Literature

Summarized in Table 1, The previous smart city literature covered a wide range of domains dealing with the conventional city infrastructure, the transportation system, the physical environment, the government service, and the emerging service or system. First, the smart city seeks to improve efficiency in the conventional city infrastructure system. Smart energy grids help consumers and energy providers to reduce the gap between energy generation and consumption [21,19]. Improving efficiency in managing public utilities, including water, wastewater, waste management, and recycling, is another section of conventional city infrastructure management [22, 23,11,19].

A large body of literature deals with how information technology can help optimize passenger and logistic transportation. Transportation engineers have adopted a range of innovative technology to speed passenger cars on local streets and highways. Connecting various modes of the public transport system to reduce overall commute time is a good example of how smart city is introduced in transportation planning. The overall goal of transportation in a smart city is to reduce fuel and energy consumption, moving people and goods. The essence of smart transportation is monitoring and managing the flow of people and freight to improve efficiency, which reduces energy consumption and increases productivity [22, 17, 24].

Architects and building scientists explore ways to reduce energy consumption in buildings. Using 3d modeling tools, building scientists identified a range of urban form parameters to reduce energy consumption in buildings [25, 26]. Data from sensors and meters help architects understand how people behave in buildings, and the information informs the design and layout of the building and mechanical system [27].

Monitoring pollution and protecting the environment are other examples of smart city applications. Air pollution in an urban area has been a lingering challenge since Industrial Revolution. Remote-sensing and pollutant monitors in cities monitor the air quality and project the level of pollution [28-30]. The environment department administrators can better allocate resources to manage air quality and the environment with the data.

Smart governance is an application of ICT for the informed decision-making process, better collaboration among stakeholders, and thorough incorporation of public input. One of the most popular smart governance policies is 'open-data.' By making data publicly available, the local governments tend to receive more public participation and support for their policies [31-33]. Thus, based on the improved transparency in governance, the political obstacles and the unnecessary social costs are removed in improving efficiency in governance [19, 21-22].

The recent COVID-19 pandemic outbreak proves the benefit of the smart city approach in public health. Cameras and computer vision technology are useful to identify and trace infected persons [34]. Smart city technology such as transit cards successfully traced COVID-19 patients to limit the spread [35]. Video conferences and internet-based meetings reduced the chance of infection. Remote medical diagnosis and treatment reduce health care costs and improve access to health care [22, 11].

Removing geographical and physical bounds in education is another example of the benefits of adopting smart city. Using ICT tools creates more opportunities for students and teachers by freeing up typical classroom settings of paper and chalkboards. The new methods of teaching and learning attract creative people and workers [36]. As a result, the city benefits from the increased diversity or agglomeration economy. Massive open online course (MOOC) is an innovative way to deliver education to any place around the world [37]. Beyond the geographical boundaries, MOOCs intend to share high-quality education in both developed and underdeveloped countries.

Benefits of Smart City

Many benefits are adopting a smart city. The efficiency of city operation and management of its asset is greatly improved [1, 2, 38]. Smart and transparent governance promotes civic empowerment and participation while reducing the social costs in policymaking [11]. The new technology and data help scientists for more creativity and innovation [39, 40, 10]. The improved productivity attracts diverse groups of people, and the diversity generates an urban agglomeration economy [36].

Due to such economic, political, and social benefits, cities worldwide adopt the smart city as their core doctrine. In the United Kingdom, Bristol, Manchester, and Milton Keynes applied the concept of a smart city [41]. Asian cities are more enthusiastic about adopting the smart city doctrine; i.e., Songdo, South Korea [42], Masdar, UAE [14], Singapore, Taipei, Taiwan [43], Hong Kong, China [44].

Concerns on Smart City Approach

Despite many benefits, scholars also have concerns about implementing a smart city. One of the biggest challenges for using sensors and cameras in the city is privacy concerns. Monitoring and recording human activity could lead to unintended privacy infractions [6, 15, 45]. Digital data is vulnerable to hacking; thus, data security is critical in smart city implementation [15].

The smart city is often criticized as a top-down and company-driven public project diverging from its original intent of cyberdemocracy [46, 47]. The concern on centralization is the inherent limitation because the smart city concept is developed and executed by large ICT companies. Away from the initial emphasis on public interests, the data collected in smart cities is monopolized and privatized by the Privatization of data and data inequality leading to social inequality [10]. With limited access to computer and data, the lower-income households and the older age groups are likely to become data literate, which affect household income and health condition [48, 49].

Another side effect of the smart city is the total dependence on technology, a blindfold belief that ICT will solve all problems in the city and society. Scholars argue that ICT cannot create a good city [18, 10]. Rather, many flaws have been found in data collection, processing, machine learning [50, 51].

Table 1. Domains in Smart City Literature

Categories		Benefits	Notes
Energy and Utility	water, wastewater, waste management, electricity, fuel	Utility meters monitor energy and utility consumption real-time and notify consumers and producers to reduce overall utility consumption and production costs.	[11, 19, 21-23]
Infrastructure	Streets, highways, water main, elec. grid,	Sensors identify failure of physical system. The data collected from maintenance help managers to anticipate the failure and reduce maintenance costs.	[11, 19, 22, 23]
Transportation	Public transit, logistics, traffic signal	Data on public transit ridership help transportation planners to predict the transportation load and to distribute the buses and trains accordingly. Cameras and sensors identify the congested areas and control the traffic signal to reduce traffic jam.	[22, 17, 24]
Built Environment	Building Layouts, construction, operation	Environmental simulations and computer modelling allow architects and engineers to find the optimal size of buildings and layouts of buildings.	[25-27]
Natural Environment	Park, air quality, pollution	Remote-sensing and pollutant monitors identify the source and the area of pollution and allocate resource for air quality management.	[28-30]
Government Administration	civic input and participation, open data, feedback loop	e-governance and open data policies improve transparency in governance. With civic input and public participation, politicians and administrators can make informed decisions.	[19, 21, 22, 31-33]
Health	public health, remote diagnosis	Remote medical diagnosis and treatment reduces the cost of health care and improve the access to health care.	[11, 22, 34, 35]
Education	MOOC, metaverse interface	ICT tools provides more opportunities for students and teachers. Massive open online course delivers high quality education in both developed and underdeveloped countries.	[36, 37]

Smart City in Urban Design Discussion

Smart City in Urban Design

While ICT scientists and city managers scramble for smart cities, few urban designers adopted smart city technology in understanding the physical environment of cities. Urban design is primarily concerning the configuration of the building and public space and the public life in plazas and squares [52-54], streets, and sidewalks [53, 55-59]. Since these urban design studies explore the quality of the environment and the social activities in these spaces, qualitative research methods, such as participant observation, interviews, and mapping, are widely accepted. Thus, few have dealt with smart cities in urban design.

Despite the slow adaptation of new technologies, urban designers began to apply smart city tools and research methods in understanding urban spaces as shown in Table 2. Application of smart city technologies are tested in various areas in urban design; 1) monitoring people's use and activity in public space, 2) documenting the physical settings of public space, 3) finding the optimal urban form with environmental simulation, 4) operationalizing people's perception, and 5) identifying potential space vulnerable for a crime. The following section will discuss the branches of smart city discussion and the application of ICT in urban design.

Monitoring Use of Public Space Using Sensors and New Analytical Tools

Williams et al. [60] devised a set of benches and camera stands to observe how people use urban public space. Both stationary and pedestrian activities are recorded via the sensors and cameras embedded in the devised benches. By observing the duration of stay, Williams et al. [60] are able to differentiate the activities, passing by, expressing curiosity, and staying for social activities. The study followed the protocol from public life study pioneered by urban designers, including Gehl [61], Whyte [52], Appleyard [56], and more.

Lee [62] further explored the pedestrian data collected from computer vision monitors in relationship to the social activities in Dilworth Park, Philadelphia. He pointed out that often quantitative data is well received by urban designers because they are primarily concerned with the quality of places rather than the quantity. Thus, by nature, urban designers tend to ignore the data and rely on insight and experience. However, controlling the weather data and the thermal comfort index with the pedestrian traffic and the correlation between the entry and exit, the pedestrian data showed statistical significance.

As a Design Tool

Urban designers increasingly value the use of data in the process of designing the physical environment of cities. Caldwell et al. [63] presented how data collected from the web, including Facebook, Twitter, and other social networks, helps prioritize the urban issues and the local needs. The use of a web-based survey is an integral part of collecting public opinions for the design proposals. Williams [60] promotes using data in both urban design and the public participation process. She argues that the birth of public health and urban planning is based on data and

then-innovative research methods, including mapping. Similarly, in current states, fine-grain data is another technological breakthrough to advance public action. Foth [64] stresses that digital technology is essential to create public space integrating diverse economic and social classes.

Environment Performance Simulation of Urban Form

Urban form scholars have investigated the more energy-efficient configuration and layout of buildings and neighborhoods with the help of smart sensors and environmental simulation tools. Ratti et al. [65] revisit the simplified arrays of structures, including pavilions, slabs, terraces, terrace-courts, pavilion courts, and courts in an arid climate. Among the six archetypes of the urban fabric, the courtyards perform the best in terms of daylighting and building development density. In addition to light and thermal environments, airflow and ventilation environments are smart city researchers' foci [66]. Using computer fluid dynamics (CFD), the air movement and the pollution dispersion in the urban street environment are simulated.

Monitoring Urban Environment

Galle et al. [67] investigate the biodiversity of urban forests in cities aggregating tree inventories from cities including Cambridge (USA), Vancouver (Canada), Buenos Aires (Argentina), Bologna (Italy), Amsterdam (The Netherlands), Oslo (Norway), Paris (France), and Melbourne (Australia). Comparing the diversity indices, the Shannon Index, and the Simpson Index, the researchers are able to understand the level of biodiversity in the eight cities. And monitoring the status of biodiversity in urban forests can minimize maintenance expenses and control the risk of mass mortality of urban forests.

Monitoring Walkability

Walk Score measures the aspects of neighborhood walkability. It assigns the score based on amenities, including retail stores, community programs, the configuration of streets, and pedestrian connectivity. Walk Score is a way to quantify pedestrian environment [68]. Miranda et al. [69] explored how people navigate the city using GPS data. The study presents evidence that pedestrians do not always take the shortest route; rather, pedestrians are willing to take a longer walk to enjoy desirable destinations and avoid undesirable stops.

Real-Time Population Distribution

Location-based service is a new approach to measure the real-time population density in cities. Ratti et al., [45] tested cell phone data to estimate the spatial pattern where people locate the most in Milan, Italy. This helps to fine-tune the supply of public and commercial services based on actual demand. Public transportation and traffic control can be optimized based on the data. Similar studies are conducted in other cities, including Rome [70], Boston [71], Shanghai [72], Suzhou [73], and Shenzhen [74].

Operationalizing Human Perception

Investigating how people understand the built environment has relied on the conventional data collection method such as interviews and surveys. Zhang et al. [75] developed an algorithm mimicking the way people perceive and evaluate urban places. Zhang et al. adopted the online volunteer survey of how people feel about the Google Street View images. Using the survey data as the training data for machine learning. The researchers identified the streets that are safe, lively, beautiful, wealthy, depressing, and boring in the urban context of Beijing, China.

Predicting Perception of Safety

Zhang et al [76] measure the perceived level of fear from the urban environment. The researchers applied the perceptual ratings from online volunteers from a previous study [77] using computer vision technology to identify the environmental stimuli that affect safety or fear. They analyzed the level of safety at the census block group in Houston based on Google Street View. Then, Zhang et al. [76] were able to categorize neighborhoods as 'well-maintained, 'cues-to-care', and 'physical-disorder.' The paper expands research further by comparing the calculated score of safety and the crime rates and concludes that the safety store and the crime rate are highly correlated.

Preventing Crime

Chiodi [78] argues that online participation based on information and communication technology (ICT) can improve participatory planning for Crime Prevention through Urban Design and Planning (CP-UDP). Using the internet-based portal and increased civic participation, she points out public policy decisions can be made with input from more citizens and political representatives. Laufs et al. [79] propose smart city technology related to security has more significant potential to improve the conventional security system. Adding new sensors, automating an old system, and utilizing crowdsourcing are the three categories that can significantly improve crime prevention in public space.

Table 2. Domains in Urban Design Related to Smart City

Categories	Benefits	Adopted Technology	Notes
Public life in public space	Automate manual observation	Computer vision, camera, GPS	[60, 62]
As a design tool	Prioritize the urban issues and the local needs using data from web	API, data crawling	[63, 64]
Documenting physical environment	Unravel relation between physical setting and human behaviors	Remote-sensing, open data	[67-69]
Optimal urban form	Environmental simulations allow evaluate the energy efficient configuration and layout of buildings	CFD, daylight simulation	[65, 66]
Perception Study	Operationalize human perception on urban spaces	Web-based survey, computer vision	[75-77]
Crime Prevention	Identify the areas vulnerable for crime	Sensors and cameras	[78, 79]

Summary of Survey

Innovation in Research Methods

For many reasons, researchers have adopted smart city urban design tools to replace the traditional research tools. Urban designers often apply new technologies to replace manual observation and interviews [62, 76, 80]. The conventional data collection methods are often expensive [76, 80]. Training interlocutors and surveyors to the same skill level are difficult [80]. Therefore, few urban design studies have expanded to cross-sectional studies examining urban design policies' generalized effect [80].

Expanding Research Boundary

Smart city tools allow urban designers to verify the theories in urban design. Public life studies investigating the relationship between physical settings and social activities tend to be difficult to replicate. The use of new sensors and pedestrian count data patterns helps us verify the urban design theories [60, 62]. Using GPS signals expanded the boundary of knowing how people travel in greater detail. Conventionally, pedestrian behavior was observable in public spaces, streets, parks, and plazas. The GPS data helps us understand pedestrian behavior beyond the existing boundary (i.e., [45, 69]).

Improving Public Space Operation and Management Efficiency

Many previous studies investigated ways to improve operational efficiency using advanced technology. The computer simulation helps planners and architects to find the optimal layout of buildings and open spaces [65, 66]. Sensors and cameras are useful to improve public safety in urban spaces by reinforcing conventional policing tactics [78, 79]. Documenting and monitoring natural and built environments can help city managers expect risks and issues and minimize maintenance expenses [67, 69].

Quality of Place

The application of smart city concept in urban design is seemingly promising; however, existing studies do not share convincing evidence to assess the quality of place. Some urban designers explored the dimension of human activities in place [60, 62]. However, they did not address the relationship to the ultimate independent variable in urban design, the effect of the physical environment and the quality of place.

Research Gap

While introducing innovative technology in urban design is a noble approach; however, the challenges are how to fill the gap between the quality of place and the quantified version of place and the discrepancy between the reality and the abstract version of the reality. For example, the studies applying computer vision to replicate how

people perceive environmental elements are innovative and exciting (e.g., [76]). However, the current level of technology cannot capture the fine grain of environmental settings; rather, the technology can roughly understand the abstract version of reality. The sensors are not smart enough to understand the qualitative aspect of public space study at the present state. Thus, validating the abstract version of reality, or numeric value of places, is a necessary next step.

The privacy issue has been identified as one of the concerning issues in smart cities. In urban design research, however, privacy in public space has not been addressed enough. Smart city scientists raise the potential threat to privacy by monitoring human activities in public and private space and by the vulnerability of digital data for hacking [6, 15, 45]. The sensors, meters, and cameras in smart cities tend to store individual's information in raw digital format. Due to privacy issues, the application of new technology in public space research is repeatedly rejected. A systematic review of the current issues on privacy and a new set of protocols in public space research is required to advance smart city technology in urban design.

Conclusion

The smart city is a fledgling doctrine in urban design. Due to the qualitative-oriented characteristics of urban design, the information technology and the quantitative-based approach are baby steps in research of public life and the physical environment. Challenges in adopting new technology in urban design include 1) the verification of numeric data on social activities in public space, and 2) the privacy and ethical issue dealing with a human subject in public space.

Despite the challenges, a growing number of urban designers and urban form researchers experiment with a wide variety of technologies:

1. Monitoring people's use and activity in public space
2. Documenting the physical settings of public space
3. Finding the optimal urban form with environmental simulation
4. Operationalizing people's perception
5. Identifying potential space vulnerable for a crime

It is a new opportunity to untangle the complex mechanism of human behavior in public space and a chance to explore sustainable urban forms.

This study presents several leads in the intersection of smart city and urban design research. First, the data from smart sensors and cameras must be verified by the actual human behavior that is meaningful in activating places and urban design research. It is necessary to compare notes among smart city scientists and urban designers. Second, a study to set a privacy protocol in monitoring and public space is another essential task. Third, smart city study needs to expand measuring the quality of place both in the dimension of human activities and physical settings.

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