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# Information and communication technology (ICT), digital divide and urbanization: Evidence from Chinese cities

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ABSTRACT

Information and communication technology (ICT) is a key driver of urbanization but can also create the digital divide that hinders urbanization. The study aims to explore the dynamic relationship among ICT, the digital divide and urbanization in China. Employing data collected from prefecture-level cities in 2017, this study first constructs a composite urbanization index through principal component analysis (PCA), then applies a geographically-weighted regression (GWR) model and partial least squares structural equation modeling (PLS-SEM) to probe the effects of ICT on overall urbanization. The results suggest that ICT positively affects urbanization and directly improves urbanization levels and efficiency. The application of mobile phones is an indispensable tool for future urban development. However, there are digital divides among areas. Less-developed cities lag behind well-developed ones due to their poor basic conditions and low-levels of ICT perception among residents. Therefore, knowing how to boost ICT development, narrow the digital divide and promote urbanization is of great importance. The essential role of the government in urbanization and technological progress is emphasized, and it is believed that government-led ICT-based urbanization can alleviate the digital divide and achieve balanced regional development.

## 1. Introduction

Urbanization involves the redistribution of rural-urban populations, rearrangement of arable and construction land, and changes in production modes and social styles [1]. It is also believed that urbanization is accompanied by technological advancement because information and communication technology (ICT) can facilitate the modernization process. In developed and rapidly-developing areas, ICT has always been considered to be a stimulus of social progress and has played an essential role in promoting economic growth [2,3]. In less-developed areas, especially poverty-stricken regions, ICT is a key tool that can help to reduce poverty through generating job opportunities and improving per-capita income [4,5]. It is obvious that ICT exerts various positive impacts on regional development.

However, due to their different developmental stages, exogenous environments and basic conditions, not all cities reap the benefits of ICT immediately and directly. There are differences in how cities use and develop ICT, which are often called the digital divide [6]. Because of the huge inequalities in accessing and using ICT, digital divides naturally occur among cities and have also become problematic for regional development [7]. Although ICT empowers people to obtain information more rapidly than ever, which has drastically changed the economic and political dimensions of society [8], the digital divide is an obstacle to healthy urbanization in the information age. It can prevent cities from enjoying the equal ICT opportunities that can boost urbanization. Hence, increasing the positive effects of ICT and narrowing the digital divide are urgent issues that must be solved as part of the urbanization process [9]. To this end, the relationships between ICT, the digital divide and urbanization must be clarified.

A number of studies have analysed the impacts of ICT on the individual [10,11] or national levels [12–14] and confirmed its positive effects on personal life [15], financial development [16] and organizational operation [17]. Based on these studies, the present study intends to expand existing research by analysing the impacts of ICT on urbanization. It aimed to comprehensively understand ICT's influences on people, space, the economy and society. From another angle, different degrees of access to and use of ICT generate digital divides, which will result in different levels and efficiencies of urbanization. Referring to extant studies associated with the digital divide, most probe its determinants (e.g. residential income, education level, individual skills

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and habits, etc.) [18,19]. Few studies have explored the repercussions of the digital divide, which the present study will investigate. Considering these research gaps, it is believed that the topics of ICT and the digital divide in the context of urbanization are worthy of investigation.

Being an emerging economy, China has the opportunity to undergo an ICT revolution. Currently, China is the world's largest telecommunications market in terms of the total number of mobile phone subscriptions and has an individual internet usage rate higher than the global average [20]. ICT has permeated both urban and rural China [21] and has greatly reshaped people's lives in many aspects [22]. Recently, the concept of "new infrastructure" has been put forth in China with the implementation of ICT, indicating that ICT development is crucial to China's future development. The term "new infrastructure" refers to a new type of infrastructure construction that differs from conventional ones (e.g. highways, railroads, airports). In the year 2020, the scope of new infrastructure was officially determined to include 5G base stations, the industrial Internet of Things, artificial intelligence (AI) and data centres. Against this backdrop, it can be concluded that the acquisition, integration and innovation of ICT is key to boosting economic and social development in China in the coming years.

This study aims to analyse a worldwide issue using China as an example, and attempts to propose a solution with universal significance. To achieve the goal of this research, the dynamic relationships among ICT, the digital divide and urbanization were established, and 296 prefecture-level cities in China were selected for sampling. Then, using principal component analysis (PCA), a geographically weighted regression (GWR) model and partial least squares structural equation modeling (PLS-SEM), specific ICT indicators were applied and a complex urbanization index was constructed to solve the following research questions:

(1) What is the relationship between ICT and urbanization in China and what is the spatial distribution of the digital divide?
(2) How does ICT generate the digital divide and affect urbanization levels and efficiency, and what actions can boost ICT development, bridge digital gaps and accelerate urbanization?

This study makes some novel contributions to the existing research. First, it offers a different research perspective. Compared with studies which concentrate on the economic benefits that ICT brings [23,24], this study focuses on ICT's effects on urbanization, which is a relatively new perspective. It also constructs relationships between ICT, the digital divide and urbanization that can be used in similar studies. Second, this study uses a different research scale to what has been used before. Studies of ICT's effects on regional development have mostly employed country-level data [25,26]. The present study focuses on China's situation and uses prefecture-level data, which is rare in recent studies. Third, it synthesizes several research methods. The PCA technique can transform complex data into a smaller set of variables, which is useful for constructing a composite urbanization index [27]. The GWR model improves general regression models by incorporating spatial elements and geographic context [28]. The distribution of the digital divide can also be presented visually for better understanding. The PLS-SEM is widely used to analyse specific effects among multiple factors within a small dataset [29]. These methods are used to comprehensively answer the research questions and provide a reference for other researchers investigating ICT-related issues.

The rest of this article is structured as follows. Section 2 reviews the literature on the research topic and establishes a relationship between the research objectives. Section 3 presents the data and methods used. Section 4 reports the results. Section 5 discusses the results and outlines suggestions for ICT-based urbanization. Section 6 draws conclusions and lists limitations.

## 2. Literature review

### 2.1. Urbanization in the context of ICT

Urbanization is a global phenomenon. Studies on the influential factors that drive the development of urbanization mainly relate to population, industry and policy [30]. Plus, land urbanization, economic urbanization and social urbanization have also drawn intense attention [31]. Moreover, ICT is regarded as a stimulator of urbanization due to its ubiquitous nature in urban systems. Therefore, in an information society, *urbanization* is endowed with new connotations. In terms of *population urbanization*, ICT brings many employment opportunities to both rural and urban citizens [32], which vastly facilitates labour mobility. The transformation of citizens from rural to urban is no longer the best index of population urbanization. ICT-related job opportunities attract rural people to work in rural areas and help local governments increase fiscal revenue [33], narrowing the gap between rural and urban areas. *Land urbanization* means that urban built-up areas are developing in a proper and orderly manner. Since a major feature of ICT is reducing transaction costs and improving information flow, the agglomeration of e-villages (e.g. Taobao villages in China) means that the boundaries between cities and rural areas are less distinct [34]. Moreover, because ICT is widely used in urban planning, urban forms and structures are gradually transformed. The notions of mixed and sustainable land use and compact cities have emerged in the ICT context [35,36]. *Economic urbanization* is a prerequisite for urbanization, and the fact that ICT boosts economic growth is undeniable [37]. Hence, it is reasonable to consider that ICT cultivates new points of economic growth and creates digital economic models. The essence of *social urbanization* is to improve the overall levels of education, healthcare, individual welfare, social security and the built environment, etc. ICT is a good approach to promoting social improvement. For instance, e-learning and telemedicine allow residents of remote areas to enjoy advanced education and healthcare. The popularization of mobile phones gives people, regardless of gender or social status [38], access to information that they could not receive before.

The four dimensions of urbanization in the context of ICT are shown in Fig. 1. The concept of the urbanization process changes when ICT is considered. This study will comprehensively evaluate urbanization as affected by ICT, by constructing a complex urbanization index comprised of population, spatial, economic and societal factors.

### 2.2. Urbanization and the digital divide

While the technological revolution yields huge dividends for regions with good infrastructure, less-developed regions are struggling to keep pace with ICT and regional development [39], which can produce a digital divide between areas. The digital divide has a close association with insufficient access to ICT [40]. When discussing the benefits of ICT, the influences of the digital divide are always mentioned. During the rapid process of urbanization in the information age, the effects of the digital divide must not be overlooked and have become important issues for global policy-makers [41].

As discussed above, there are four aspects to urbanization in the context of ICT, and the digital divide may influence each of them. In terms of population and social urbanization, the digital divide disempowers people in poor regions [42]. They may not have the capability to use ICT such as smartphones and internet, which may hinder them from leaving their poor home village to find a better life [43]. Meanwhile, people who have ICT capabilities can promote their social status by leaving poor areas and obtaining better-paying jobs. Moreover, the digital divide generates social exclusion and reinforces social stratification, reducing people's overall degree of life satisfaction [44,45]. In terms of land and economic urbanization, the digital divide leads to unequal distributions of resources [46], which restricts development in some area in terms of urban construction and economic growth [26,47].

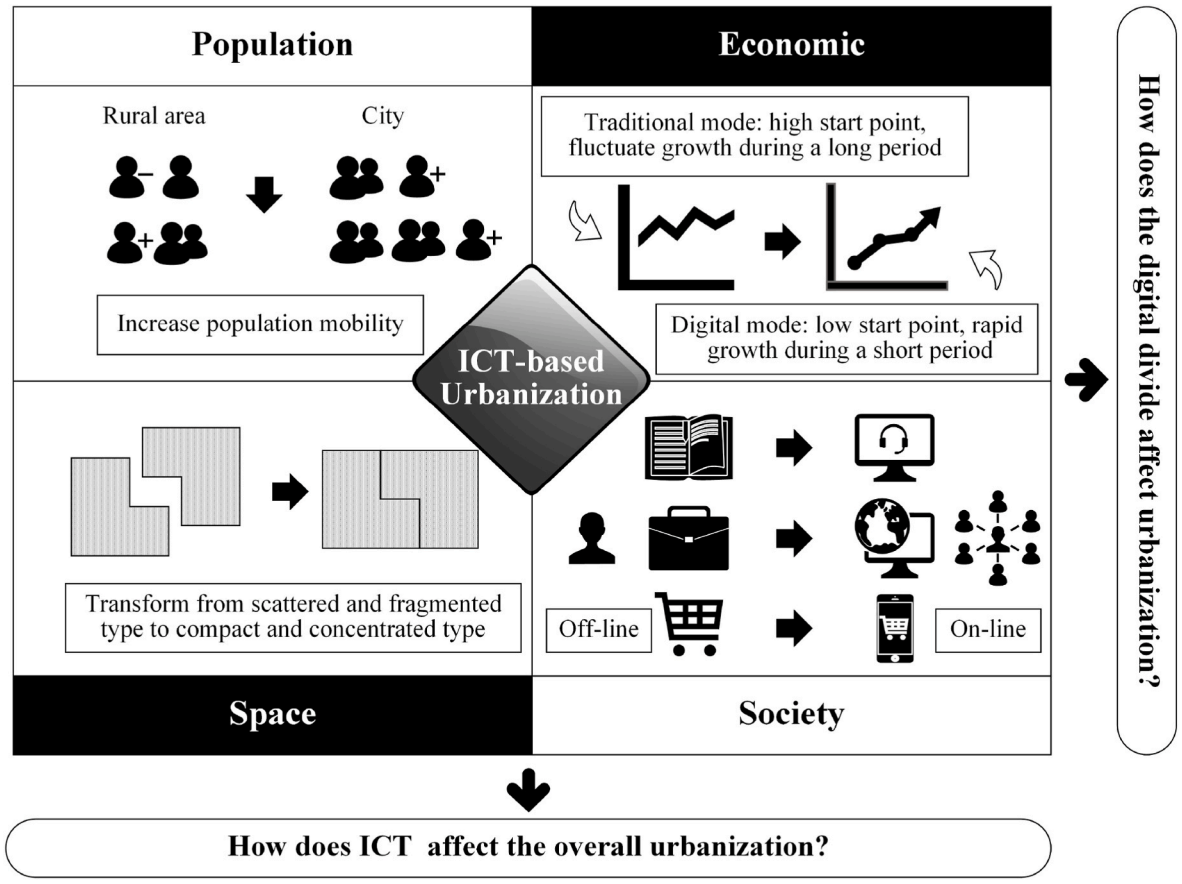


**Fig. 1.** The four dimensions of urbanization in the context of ICT.

It can be concluded that the digital divide deepens regional inequality in many aspects and impedes overall urbanization. However, the digital divide can change along with the transformation of ICT and regional development patterns [46]. When areas have equal ICT capability and balanced regional development, the digital divide will gradually narrow. Conversely, when they do not, the divide will widen.

### 2.3. Measurement of ICT and the digital divide

The concept of ICT is dynamic [48,49]. In the past, television, radio and fixed-line telephones were the basis of ICT. Nowadays, ICT comprises smartphones, computers and the internet. In future, big data, cloud computing, AI and other kinds of technologies that collect, process and disseminate information will become the mainstream of ICT. In consideration of the versatile and complicated nature of ICT, accurately measuring it is a challenging task [50]. Some measurement frameworks are constructed based on the ICT development index (IDI), as defined by the International Telecommunications Union [51]. The IDI consists of ICT access, use and skills indicators. It is a composite index that reflects the evolution in ICT development and indicates the level of ICT adoption. According to the definition of IDI, many studies have used specific indicators to describe the readiness, intensity and impact of ICT. Precisely, computer penetration and mobile phone subscriptions are the main indicators used to represent ICT access [52]. Internet use rates and numbers of active mobile phone users can indicate ICT use [53]. The adult literacy rate and college student enrolment ratio are proxies of ICT skills [54]. In addition, with technological progress, new indicators that symbolize ICT outcomes, such as e-commerce and e-government rates [55], are incorporated to measure the impact of ICT. In general, existing studies normally use several specific indicators of ICT or build a composite ICT index to elaborate ICT-related research questions. Among all these indicators, the ICT access indicator is fundamental, and almost all studies use it as the basic indicator [56,57]. Hence, this study will mainly use an ICT access index to measure the degree of ICT adoption.

As ICT profoundly affects economic and social development, it can also induce digital divides. There are many definitions that depict the digital divide and most rely on gaps in ICT access [44]. That is, the opportunity and ability to access ICT result in different levels of ICT adoption, thereby generating economic and social disparities. The digital divide pervasively exists among individuals, households and regions [58]; however, as with ICT, measuring it is a complex task. A major constraint is the difficulty in balancing the depth and width of the measurement [59]. Therefore, choosing the most representative indicator that captures the core of the digital divide is important. ICT access is the first stage of adopting ICT and directly reflects the digital disparities between individuals or regions. For this reason, selecting ICT access-related indicators is a feasible and efficient method of measuring the digital divide.

It can be seen from the above analysis that when measuring ICT and the digital divide, the ICT access indicator is a key factor that should be taken into account.

### 2.4. Dynamic relationships among ICT, digital divide and urbanization

Although ICT and the digital divide are always mentioned simultaneously [60], few studies combine the two concepts to demonstrate their effects on urbanization. This study represents the first attempt to determine a dynamic relationship between ICT, the digital divide and urbanization to help understand how they work (Fig. 2).

As discussed above, ICT enhances urbanization but may create digital divides that hinder urban development [61]. Apart from being influenced by basic regional conditions (e.g., the infrastructure that

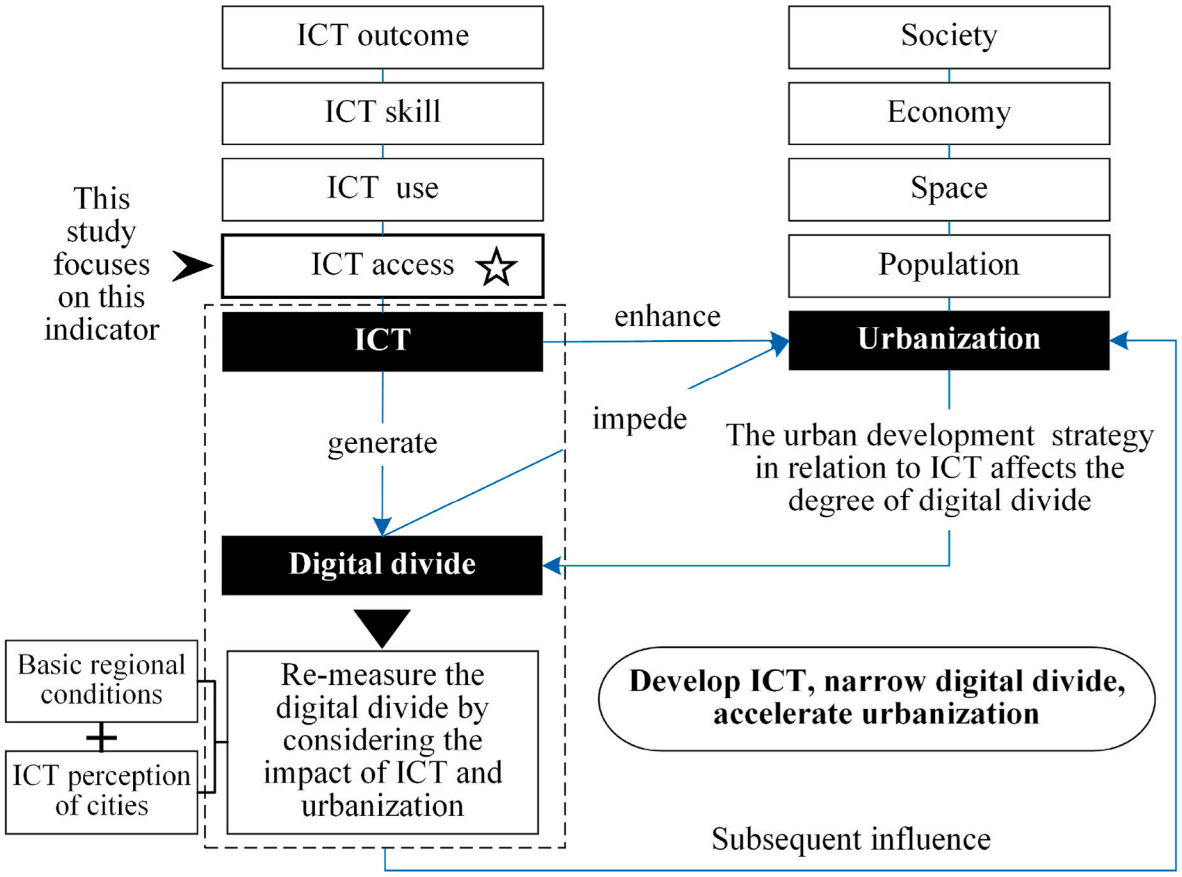


**Fig. 2.** Dynamic relationships among ICT, the digital divide and urbanization.

underpins ICT development, equal opportunity to obtain and utilize ICT), the creation of digital divides are also affected by the "ICT perception" of cities [46]. The sense of *ICT perception* refers to the functionality and practicality of ICT-related urban development strategies, the necessity and rationality of ICT-related policies, the sustainability and universality of ICT-related urban renewal plans, and so forth. A strong sense of ICT perception will dilute the negative effects of the digital divide generated by the fundamental conditions, while a weak sense of ICT perception will continually aggravate the digital divide. Regardless of whether the gap is widened or narrowed, the digital divide impacts urbanization [62].

Currently, ICT tends to generate a dilemma where good situations become better while poor ones stay poor [63]. Namely, urbanization in well-developed areas runs smoothly but lags far behind in less-developed ones. To achieve balanced urban development, ICT should play an active role in urbanization and lead to digital connectivity rather than digital gaps. Rapid updating of ICT and reductions in the digital divide should go hand-in-hand, and situations where rapid ICT development increases the digital divide must be avoided.

In the next several sections, the study will focus on an analysis of China. By looking at the case of China, the specific effects of ICT on urbanization will be generalized and actions that could narrow the digital gap will be suggested.

## 3. Data and methods

### 3.1. Data selection and processing

Based on the discussion above, a set of indicators of ICT and urbanization were selected to measure ICT accessibility and overall urbanization. The indicators were selected for their easy identification, collection and analysis features, while the number of their citations in existing literature was another important selection principle [64]. With a view to guaranteeing the availability and quality of relevant data in all samples, each indicator was checked carefully in advance. Ultimately, 2 indicators of ICT access, namely, usages of mobile phones and the internet,[1] and 12 indicators of urbanization representing the population, space, economy and society were chosen (see Table 1). Generally, the ICT and urbanization indicators that were selected were the most streamlined ones that meet the data selection criteria and the research purposes and requirements.

The study samples that were used were prefecture-level cities of mainland China. In China's administrative structure, prefecture-level cities are above county-level cities and below provinces. In order to explore the most recent information on ICT's impacts on urbanization, the sample year of 2017 was used as data from 2018 to 2019 were not yet fully published.

Finally, data on 296 Chinese prefecture-level cities in 2017 were selected (cities with missing values were excluded). All data were obtained from the *China City Statistical Yearbook*, provincial statistical yearbooks, and other public data sources, such as statistical bulletins and the internet. Then, the data were processed as dimensionless forms by applying the following equation:

$$Y_{ij} = \frac{y_{ij} - min\{y_i\}}{max\{y_i\} - min\{y_i\}} \quad (1)$$

where $Y_{ij}$ is the normalized indicator, $y_{ij}$ is the original value of the $i^{th}$ indicator at the $j^{th}$ prefecture-level city, $max\{y_i\}$ is the maximum value

[1] In this study, internet means the computer-based internet, excluding the mobile internet.

**Table 1**
Indicators of ICT and urbanization.

| Type | Indicator (units) | References |
|---|---|---|
| *Independent variables: ICT indicators* | | |
| ICT access | $x_1$: Number of mobile phone subscribers (10,000 subscribers)<br>$x_2$: Number of internet service subscribers (10,000 households) | [4,16,18,23,25,38,51,53,65] |
| *Dependent variables: urbanization indicators* | | |
| Population | $y_1$: Proportion of urban population (%) | [1,31,66–78] |
| Space | $y_2$: Urban built-up area ($km^2$)<br>$y_3$: Urban construction land ($km^2$) | |
| Economy | $y_4$: Per capita gross domestic product (GDP, yuan)<br>$y_5$: Proportion of the secondary and tertiary industry (%)<br>$y_6$: Local public budget revenue (10,000 yuan) | |
| Society | $y_7$: Number of students (10,000 persons)<br>$y_8$: Number of beds in hospitals (beds)<br>$y_9$: Persons employed in urban units (persons)<br>$y_{10}$: Urban road areas (10,000 $m^2$)<br>$y_{11}$: Length of urban sewage pipes (km)<br>$y_{12}$: Urban green land areas (ha) | |

of $y_i$, and $min\{y_i\}$ is the minimum value of $y_i$.

### 3.2. Principal component analysis

The PCA method is widely used in many research domains to construct composite indicators [79]. The objective of PCA is to transform multiple dimensions of data into a complex indicator while overcoming the problem of multicollinearity [27]. In this study, a weighted urbanization index was established by using the normalized indicator $Y_{ij}$. First, a data matrix was constructed, then a correlation matrix of variables (the results indicate that almost all variables were highly correlated) were calculated. After that, the eigenvectors were determined and the principal components were selected. It is suggested that the first two components were chosen to evaluate the weight of each variable because their cumulative proportion reached 81.6%. Finally, the urbanization index was built by de-compounding the 12 indicators into a single weighted indicator. Table 2 presents the results.

### 3.3. Geographically weighted regression (GWR) model

To better understand urbanization in China's prefecture-level cities and the ICT factors that affect it, a GWR model was employed to analyse the impact of ICT in each city.

The GWR model is a kind of local regression model, unlike global regression models such as the ordinary least squares (OLS) model, spatial lag model (SLM) and spatial error model (SEM). Global regression models assume that the relationships between independent and dependent variables do not vary spatially [80]. The GWR model is an improvement on traditional global models. It reflects the spatial differentiation of parameters in each location, rather than representing spatial stationarity [81]. The GWR model can be expressed as follows:

$$y_k = \beta_{k0} + \sum_{m=1}^{n} \beta_{km} x_{km} + \varepsilon_k \; k = 1,\ 2,\ \ldots,\ p \tag{2}$$

where $y_k$ is the urbanization index for the dependent variable at location $k$, $x_{km}$ is the $m$th independent variable at location $k$, $\beta_{k0}$ represents the intercept term at location $k$, $\beta_{km}$ represents the $m$th local regression coefficient for the $m$th independent variable at location $k$, and $\varepsilon_k$ is the error term.

In the GWR model, the weights of the explanatory variables are varied during the regression process. The estimated parameter values for each explanatory variable at every location are determined as follows:

$$\widehat{\beta}(u_k,\ v_k) = (X^T W(u_k,\ v_k) X)^{-1} X^T W(u_k,\ v_k) Y \tag{3}$$

$$X = \begin{bmatrix} 1 & x_{11} & \cdots & x_{1,\,n} \\ 1 & x_{21} & \cdots & x_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ 1 & x_{p1} & \cdots & x_{p,\,n} \end{bmatrix},\ Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_p \end{bmatrix} \tag{4}$$

where $\widehat{\beta}(u_k,\ v_k)$ is a $n \times 1$ vector of the parameter estimates, representing the estimated value of $\beta$, $X$ is a matrix of the independent variables ($p \times n$), $W(u_k,\ v_k)$ is the spatial weight matrix ($p \times p$), and $Y$ is a $p \times 1$ vector of observations of the dependent variable. A kernel function should be specified to calculate $W(u_k,\ v_k)$. A commonly-used kernel function is the bi-square function.

### 3.4. Partial least squares structural equation modeling (PLS-SEM)

The PLS-SEM approach can be applied to conduct explanatory research when there are multiple relationships among multiple variables and the data are non-normally distributed [82,83]. To further explore the specific effects of ICT on different aspects of urbanization, a PLS-SEM comprised of indexes of ICT, urbanization level, socio-economic condition, and infrastructure construction was built. The conceptual

**Table 2**
Results of PCA of the urbanization index.

| Number | Value | Difference | Proportion | Cumulative value | Cumulative proportion | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.276 | 6.758 | 0.690 | 8.276 | 0.690 | | | | | | | |
| 2 | 1.518 | 0.842 | 0.127 | 9.793 | 0.816 | | | | | | | |
| 3 | 0.675 | 0.232 | 0.056 | 10.469 | 0.872 | | | | | | | |
| 4 | 0.444 | 0.146 | 0.037 | 10.913 | 0.909 | | | | | | | |
| 5 | 0.298 | 0.013 | 0.025 | 11.211 | 0.934 | | | | | | | |
| 6 | 0.285 | 0.092 | 0.024 | 11.496 | 0.958 | | | | | | | |
| 7 | 0.193 | 0.078 | 0.016 | 11.689 | 0.974 | | | | | | | |
| 8 | 0.115 | 0.033 | 0.010 | 11.804 | 0.984 | | | | | | | |
| 9 | 0.081 | 0.030 | 0.007 | 11.885 | 0.990 | | | | | | | |
| 10 | 0.051 | 0.007 | 0.004 | 11.936 | 0.995 | | | | | | | |
| 11 | 0.044 | 0.025 | 0.004 | 11.980 | 0.998 | | | | | | | |
| 12 | 0.020 | – | 0.002 | 12.000 | 1.000 | | | | | | | |
| *Eigenvectors (loadings):* | | | | | | | | | | | | |
| Variable | PC 1 | PC 2 | PC 3 | PC 4 | PC 5 | PC 6 | PC 7 | PC 8 | PC 9 | PC 10 | PC 11 | PC 12 |
| $Y_1$ | 0.205 | 0.507 | −0.060 | 0.640 | 0.453 | 0.243 | −0.066 | 0.029 | 0.108 | 0.074 | 0.048 | 0.002 |
| $Y_2$ | 0.336 | −0.072 | −0.008 | 0.110 | −0.215 | 0.148 | −0.157 | −0.149 | −0.220 | 0.072 | −0.586 | −0.598 |
| *Weights of variables:* | | | | | | | | | | | | |
| | $Y_1$ | $Y_2$ | $Y_3$ | $Y_4$ | $Y_5$ | $Y_6$ | $Y_7$ | $Y_8$ | $Y_9$ | $Y_{10}$ | $Y_{11}$ | $Y_{12}$ |
| | 0.085 | 0.092 | 0.092 | 0.091 | 0.077 | 0.083 | 0.054 | 0.072 | 0.083 | 0.091 | 0.092 | 0.086 |

Note: Not all results are reported but they are available upon request.

framework of the PLS-SEM is shown in Fig. 3.

Population migration and spatial development are the core of urbanization; hence, urbanization indicators in association with population and space indicators were chosen to represent the basic urbanization level [30]. Only when the fundamental requirements of urbanization are achieved can it become highly efficient. Economic and social elements were considered to estimate the degree of urbanization efficiency [67] and this dimension was divided into socioeconomic conditions (including economic, education, healthcare, and employment conditions) and infrastructure construction (including the construction of roads, pipes, and green land).

It is hypothesized that ICT has direct positive effects on urbanization level, socioeconomic conditions and infrastructure construction, and the study aimed to determine the specific degree of influence on each dimension. Moreover, the study intended to probe the indirect effects of ICT on socioeconomic conditions and infrastructure construction in terms of urbanization level. In this way, the impacts of ICT on urbanization can be analysed comprehensively, which may provide a new perspective for understanding the digital divide.

## 4. Results

### 4.1. Results of the GWR model

First, the fitted results of the global regression models (OLS, SLM and SEM) and local regression model (GWR) were compared. All the global regression models were implemented in GeoDa 1.14 software. The GWR model was run in GWR 4.0 software. An adaptive bi-square kernel type was set and the Akaike information criterion (AIC) was employed to select the optimal bandwidth when using GWR 4.0. The performance of the models is given in Table 3.

According to Table 3, the AIC value decreased from −674.958 to −808.015. Among all the models, the GWR model presented the lowest AIC, suggesting that it is the most suitable one. Moreover, the $R^2$-value increased significantly from 49.7% in the OLS model to 76.1% in the GWR model. The GWR model obtained the highest $R^2$, indicating that it is superior to the general global models.

Then, the local coefficients of the GWR model were summarized (Table 4). The difference of criterion in the last column represents the geographical variability test' results. The negative figures showed that there were spatial instabilities among areas; hence, the impacts of ICT on urbanization varied by location. For the specific regression coefficients, the mean and median coefficients were positive and similar for two

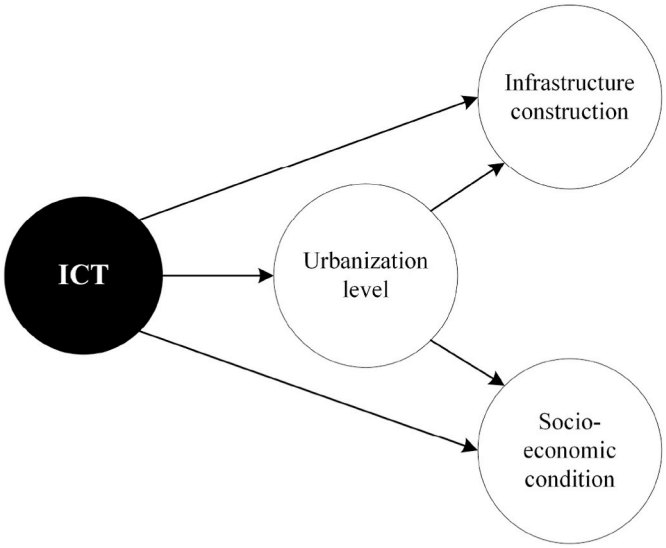


**Fig. 3.** Conceptual framework of the PLS-SEM.

**Table 3**
Comparison of the goodness-of-fit of the OLS, SLM, SEM and GWR models.

| Model parameter | OLS | SLM | SEM | GWR |
|---|---|---|---|---|
| AIC | −674.958 | −673.300 | −688.817 | −808.015 |
| $R^2$ | 0.497 | 0.498 | 0.527 | 0.761 |

variables, suggesting that mobile phone and internet use had active and consistent effects on most prefecture-level cities. However, the effect of mobile phone use was greater than that of internet use. Notably, although ICT positively affected most regions, the degree of influence varied and was even negative in some areas. These results demonstrate the dynamic relationship between ICT and urbanization. In summary, ICT enhances the urbanization process; however, it also generates digital divides, impeding the overall urbanization of some cities.

Subsequently, digital maps were drawn to visualise the influence of ICT on different cities (Fig. 4). The distributions of the regression coefficients and *t*-values of the variables can help us understand which parts of China are positively affected by ICT and which are negatively affected.

As shown in Fig. 4, the influence of ICT varied gradually from one place to another. In terms of the influence of mobile phone use, the greatest negative effects appeared in the areas of Henan, Anhui, Jiangxi, Hunan and Hubei (area 1; blue area in Fig. 4a), but were not significant (yellow area in Fig. 4b). Surrounding this area, mobile phone use exerted significantly positive effects in Beijing, Tianjin and Hebei (area 2), Shanghai, Jiangsu and Zhejiang (area 3), Guangdong (area 4) and Sichuan and Chongqing (area 5; red and orange areas in Fig. 4a, red area in Fig. 4b). On the contrary, internet use showed opposite effects in these cities. That is, significantly positive effects in area 1 and negative effects in areas 2, 3, 4 and 5 (blue, red and orange areas in Fig. 4c, red, blue and yellow areas in Fig. 4d).

The possible explanations for this phenomenon are as follows: access to mobile phones and the internet were chosen as proxies. These two forms of ICT are applied in different specific scenarios and exert different influences. For example, Chaudhuri argued that mobile technology has a strong emotional appeal in developing nations, compared with computer- and internet-based technologies [84]. Moreover, not all areas can immediately enjoy the benefits of ICT; in other words, ICT may have mixed or even negative effects on regional development [14,53].

In the past, mobile phones or computers were rare devices for ordinary families. They did not dramatically affect the daily lives of individuals. Besides, users preferred to use computer-based internet, because mobiles phones had relatively slower operation speed and were more cumbersome to navigate [85]. However, because of the fast update of ICT, mobile phones and computers became popular products, and mobiles phones are now particularly essential as they are increasingly ubiquitous [86]. Nowadays, mobile phones seem to be the more comprehensive ICT tool and can be used in a variety of circumstances. They are cheaper to buy, and more convenient to carry, compared to computers. People use mobile phones to communicate, browse the internet, pay bills [87], etc. Some studies even found that mobile phones can reduce corruption [88] and positively impact food access [65]. The rapid development of mobile phone technology (from 2G to 5G) has made phones vital tools that improve the lives of individuals in almost every aspect, which the internet alone could not have achieved. Hence, even though there are many types of ICT, it is thought that mobile phones are the most important external driver of urban development.

Because of the differences between mobile phones and the internet, their impacts on urbanization are different and vary between places. It is inferred that access to and application of mobile phones in areas 2, 3, 4 and 5 were greater and, therefore, the positive effects of mobile phones were more evident than in area 1. Mobile phones positively affect the urbanization process by broadly facilitating labor recruitment, economic growth and social improvement. The wider use of mobile phones and high internet penetration rate continuously impact cities as well as

**Table 4**
Summary statistics for varying local coefficients.

| Variable | Description | Min | Mean | Max | Lower quartile | Median | Upper quartile | Difference of criterion |
|---|---|---|---|---|---|---|---|---|
| $x_1$ | Mobile phone | −0.140 | 0.074 | 0.411 | 0.017 | 0.060 | 0.141 | −200.494 |
| $x_2$ | Internet | −0.244 | 0.030 | 0.217 | 0.001 | 0.020 | 0.065 | −403.538 |

Notes: $x_1$ and $x_2$ are treated as natural logarithms.

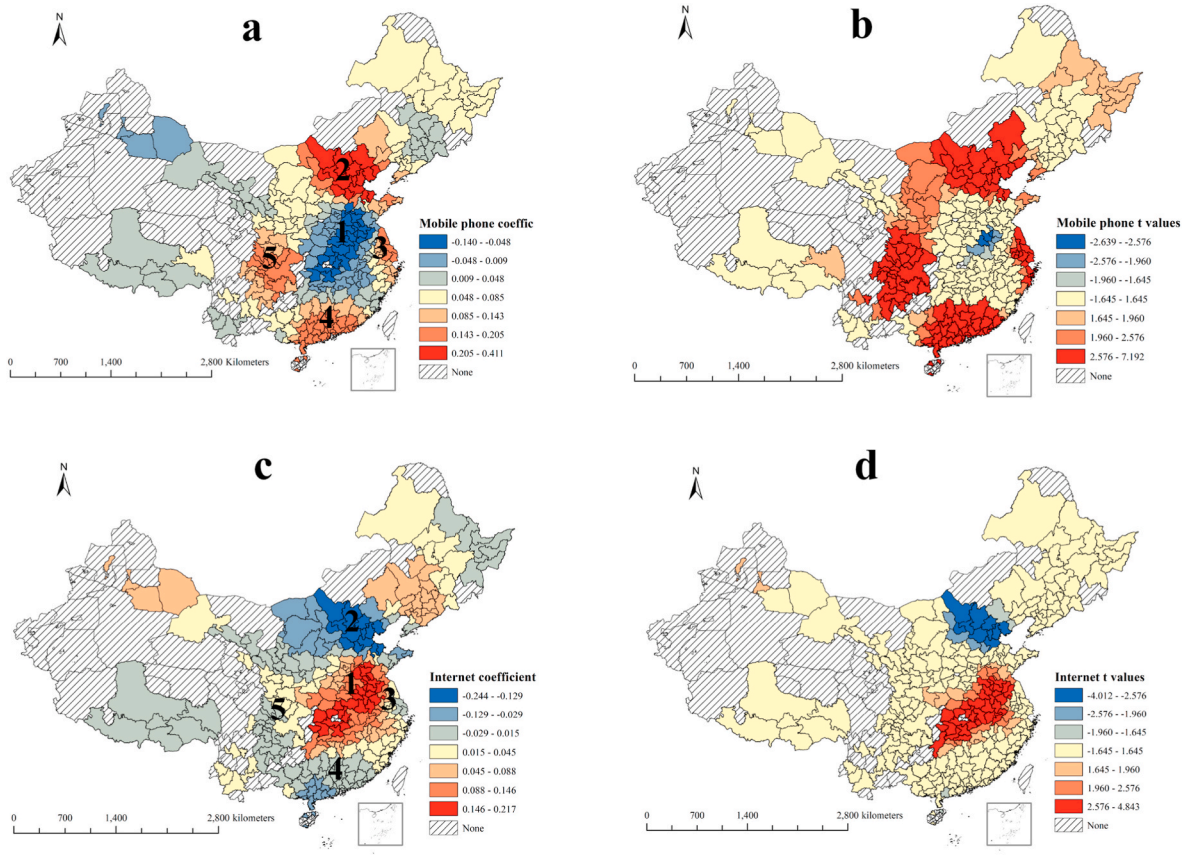


**Fig. 4.** Distribution of regression coefficients (left) and *t*-values (right) of variables $x_1$ (mobile phone use) (a, b) and $x_2$ (internet use) (c, d).

rural areas (for instance, e-commerce is very popular in villages in Zhejiang, Jiangsu, Shanghai and Guangdong). As a result, these areas represent a counter-urbanization process, because ICT provides rural regions with a new mode for development. Rapid rural and peri-urban urbanization may explain why internet access showed negative effects in areas 2, 3, 4 and 5.

Another thing that should be noted is that there are some prefecture-level cities (in Tibet, Gansu, Shaanxi and Heilongjiang) that did not reap obvious benefits from ICT. Greater attention must be paid to these areas because they are bearing the strain of the digital divide. The ICT infrastructure index (including 4G mobile base stations, wireless network access points, etc.), which is derived from China's *Internet Development Report* (2017), shows a distinct digital divide among areas (Fig. 5). It also confirms the results of the GWR model: areas 2, 3, 4 and 5 have a solid foundation of ICT infrastructure. This boosts the development of cities in these areas, but unequal access to ICT impairs the development of other cities to some degree.

### 4.2. Results of the PLS-SEM

The GWR model gives a general depiction of the ICT-urbanization nexus. By using the PLS-SEM method, more information about ICT's impacts on urbanization can be obtained. The framework of the PLS-SEM was based on Fig. 3, and the measured variables were selected from Table 1. Not all the variables were chosen, in consideration of better model performance. Plus, the non-proportional variables were treated as natural logarithms. The final selected model passed the reliability test (Cronbach's $\alpha > 0.6$) and validity test (composite reliability, CR $> 0.7$, average variance extracted, AVE $> 0.5$), and the latent variables in the model had a high variance inflation factor (VIF $> 0.2$), which all demonstrate the robustness of the model. Furthermore, the bootstrapping analysis also confirmed the stability of the model. All the estimated path coefficients were statistically significant at the 1% level. The results of the PLS-SEM are shown in Fig. 6.

ICT directly and positively affected urbanization level, socioeconomic conditions, and infrastructure construction, with path coefficients of 0.709, 0.774, and 0.307, respectively. ICT strongly influenced the basic dimensions of urbanization and improves socioeconomic status, but had a relatively weak impact on traditional infrastructure. The indirect effects of ICT on socioeconomic conditions and infrastructure construction via urbanization level were 0.153 ($0.709 \times 0.216$) and 0.491 ($0.709 \times 0.693$). Although the indirect ICT impacts were positive, their degrees were different from those of the direct impacts.

Among the relationships between ICT, urbanization level and

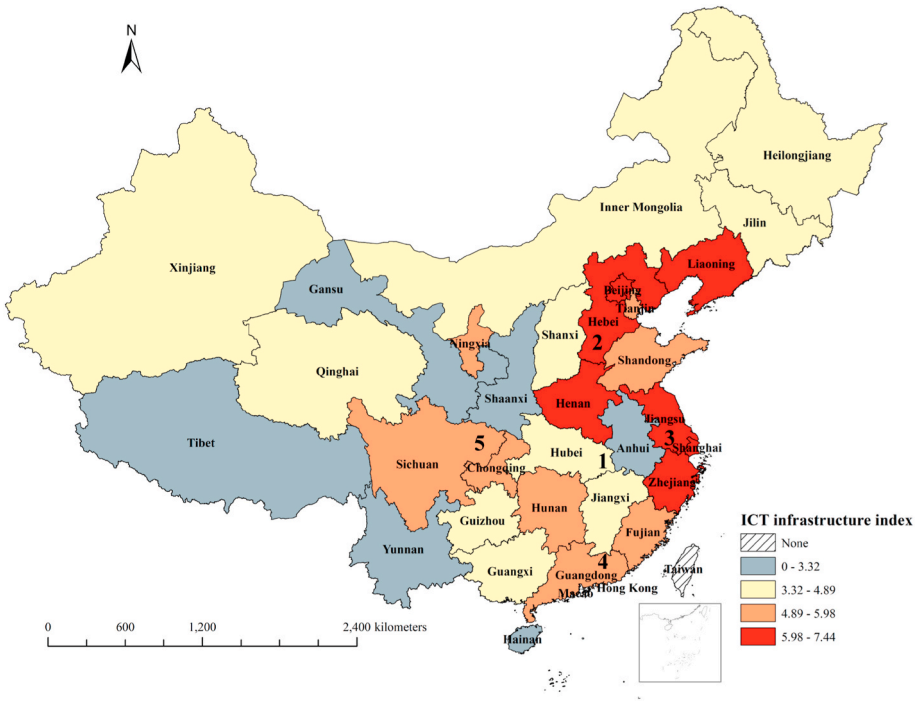


**Fig. 5.** ICT infrastructure index of China's provinces in 2017.

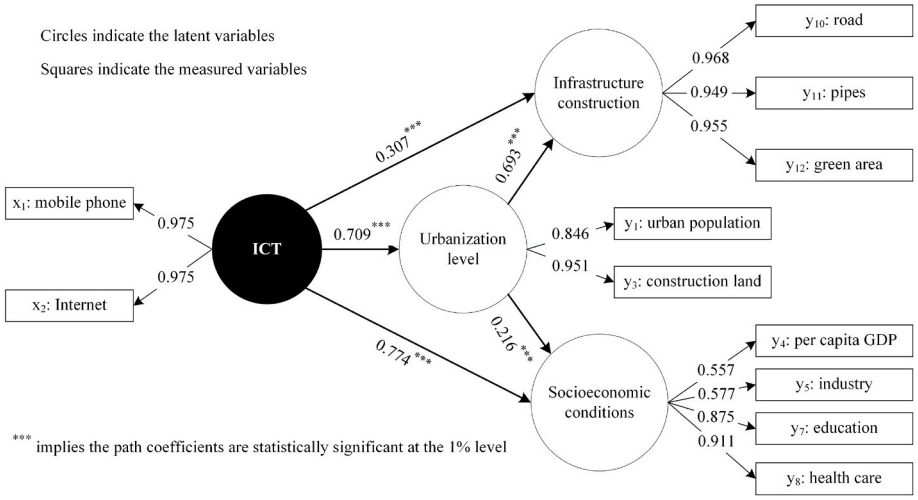


**Fig. 6.** The PLS-SEM of ICT, urbanization level, socioeconomic conditions and infrastructure construction.

socioeconomic conditions, it was found that when the factors of population mobility and urban form reshaping were included, the positive ICT effects were largely reduced. The digital divide is thought to be the reason. While ICT definitely promotes economic and social life, due to cities' different conditions and levels of development, ICT access and ICT use, such positive effects vary. Well-developed areas enjoy ICT-related benefits, while less-developed areas seem to be left out. Another thing to note is that, among the relationships between ICT, urbanization level and infrastructure construction, the indirect ICT effects on infrastructure were raised. This is because local governments have long considered the construction of traditional infrastructure to be an indispensable part of urban development. Employment of ICT, as well as rapid urbanization, are more conducive to traditional infrastructure. However, it is believed that in the near future, while traditional infrastructure construction is maintained, massive construction of ICT infrastructure will become a trend.

### 4.3. Compare results with related studies

The results of the GWR and PLS-SEM show various effects of ICT on urbanization that are consistent with related studies. The results can be summarized as follows: First, different types of ICT generate different outcomes. Many studies have shown different impacts of mobile phones and internet on economic activities [4]. For example, Nguyen found that mobile usage positively affected financial development while internet usage negatively affected it in 109 countries from 1998 to 2017 [89]. Donou-Adonsou reported a positive effect of internet on economic growth in 45 Sub-Saharan African countries during 1993–2015, but mobile phones had none [90]. Second, there are disparities between areas in reaping ICT benefits, which impede socioeconomic development and urbanization in some areas. Van Ark documented that the ICT's contributions to the United States were higher than those to the European Union (EU) over the period 1995–2004 [91]. Çilan argued

that socioeconomic development is closely related to ICT and the problem of the digital divide in EU must be addressed to achieve better development [92]. Rath emphasized that the digital divide that exists between developed and developing areas needs to be reduced from a political perspective [41]. Third, the long-term effects of ICT may change the digital divide situation and exert positive effects on urbanization. Some studies have confirmed that the effects of ICT are transformed over time. Brynjolfsson suggested that the long-run contributions of computerization to productivity are larger than its short-run effect [93]. Nguyen also pointed out that mobile usage has positive impacts on financial development but no impact in the short run [89]. Hence, it is supposed that when a mature ICT is applied in an area, the full benefits are obtained. Meanwhile, when an area applies new ICT, its effects may be ambiguous and a digital divide occur due to unequal access to and use of ICT. Four, a solid ICT infrastructure is essential in narrowing the digital divide and boost urbanization. Some studies have demonstrated a significant role of ICT infrastructure in catalysing economic growth [94,95]. The essence of using ICT is to help reduce inequity, and equal access to ICT is the first step to bridge the divides between areas. When the scale of ICT infrastructure construction reaches a critical size, the digital divide can be narrowed and balanced regional development may occur.

In the next section, the results of the two research methods are combined to provide some targeted strategies for reducing the digital divide and speeding-up ICT-based urbanization in cities.

## 5. Discussion

In the above analysis, dynamic relationships among ICT, the digital divide and urbanization were established. The GWR and PLS-SEM models support the overall positive effects of ICT on urbanization, and also verify the presence of the digital divide in Chinese prefecture-level cities. Regional divergence combined with technological disparities between areas have led to the digital divide, which continuously affects urbanization, leading to unbalanced urban development. Judging from the current situation, such unbalanced patterns have not been alleviated by ICT progress; instead, they have been exacerbated by the digital divide.

The concept of the digital divide is easy to define and its negative impacts on urban development are obvious. However, these issues cannot stereotype the digital divide. The digital divide can be mitigated when technological advancement that takes regional differences into account is pervasive, and when cities fully utilize ICT to promote balanced development. The changing impacts of the digital divide on urbanization are hard to estimate accurately. We cannot articulate the specific degree of the effect of the digital divide that impedes urbanization and produces the existing imbalances among cities. Nevertheless, suggestions that may help mitigate the adverse influences of the digital divide can be provided.

The role of the government is vital during urbanization, and they can also be a driver of new technological applications. On one hand, government-led ICT-based urbanization provides a new way of thinking about the development of cities. On the other hand, it is an attempt to promote the overall popularization of ICT and relieve the digital divide.

First, governments should formulate ICT-related urban development plans and increase investment in ICT projects in all areas. Considering the positive effects of ICT on urbanization in terms of urbanization level and efficiency, governments can utilize the advantages of ICT to improve the operation of cities. Because governments have administrative dominance, they can rapidly implement various ICT plans and projects in different areas. Recently, many cities have promulgated ICT action programs based on the concepts of smart cities and new infrastructure. This exemplifies governmental endeavours to deploy technology during city constructions.

Second, governments should encourage ICT innovation and accelerate the extensive application of ICT services. For example, by providing innovative subsidies for emerging ICT companies, issuing e-consumption vouchers for citizens to stimulate online shopping and helping residents, especially the elderly, to adapt to ICT society. As people form the kernel of a city, governments must put people's needs first and give them more equal opportunities in the changing world. Moreover, since mobile phone use has become widespread, it is now much easier for people to use ICT. Governments should seize this chance to build more convenient, rapid, honest and connected societies based on mobile phone use.

Third, access to ICT is a precondition for using and developing ICT; however, unequal ICT infrastructure among areas has become a major obstruction of receiving ICT benefits. Hence, the most urgent thing that governments should do is strengthen ICT infrastructure and reduce the imbalances among regions. Only when these prerequisites are met can complete ICT-based urbanization be implemented smoothly.

Finally, it is pointed out that the dynamic relationships among ICT, the digital divide and urbanization are complex and may change over time. Although the original relationships will remain relevant, new relationships may also arise. Government-led ICT-based urbanization aiming to narrow the digital divide is an example. In this way, the connection between ICT and urbanization will become stronger. Allowing ICT to penetrate into every aspect of urbanization, and regarding it as an internal element of urban development, can improve the basic conditions of regions as well as promote the ICT perceptions of cities. The next critical step is to understand how government-led ICT-based urbanization patterns occur in practice to transform the digital divide into digital connectivity and then to digital convergence.

## 6. Conclusions

ICT is definitely associated with urbanization. ICT can be a driver of urbanization; however, it can also generate digital divides that impedes urbanization. The main objective of the study was to establish a dynamic relationship among ICT, the digital divide and urbanization, and explore the specific influences of ICT on urbanization. Using ICT access and urbanization data from 296 prefecture-level cities in China from 2017, this study first applied PCA to construct a complex index of urbanization. The index included four aspects of urbanization: population, space, economy and society. Then, the study quantitatively analysed the impacts of ICT on overall urbanization by applying GWR and PLS-SEM models. The results demonstrate ICT's positive effects on urbanization and also verify the existence of digital divides. In some well-developed cities, qualified urbanization has occurred with the aid of ICT and mobile phones are an indispensable tool of great significance to future development. Meanwhile, in some less-developed cities, ICT has not benefited the urbanization process because of restrictive and poor conditions and low levels of ICT perceptions. In addition, direct effects of ICT on urbanization level and efficiency were obvious; however, when the population mobility and land restructuring elements were taken into consideration, the indirect effects of ICT on socioeconomic conditions were diminished. That is to say, some areas developed rapidly due to ICT while others lagged far behind. In conclusion, this study confirmed that the relationship among ICT, the digital divide and urbanization is dynamic and complicated. Since few existing studies have focused on these topics, these newly-defined relationships can be used for reference in future studies. The present study also reminds us to seek healthy and sustainable relationships among these factors that facilitate ICT development, narrows the digital divide and promotes overall urbanization. In the discussion section, a dominant role of the government in the ICT adoption and popularization process was highlighted. Government-led ICT-based urbanization strategies were provided for mitigating the negative impacts of the digital divide and achieving balanced urban development among regions.

There are several limitations to this study. First, the study only used ICT access indicators as proxies to measure the impact of ICT on urbanization. Although they are the basic and representative indicators of

this relationship, an in-depth analysis that considers all fields of ICT should be conducted. Second, the study did not compare the effects of ICT between years. To better explore ICT's influences in different years, panel data spanning a greater time interval would be useful. In future studies, a richer indicator system spanning several consecutive years will be established and, in addition to emphasizing the role of the government, change in individuals during the urbanization process in the information age will be analysed by collecting data first-hand through fieldwork.

## Credit author statement

Di Wang: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft; Tao Zhou: Validation, Writing – review & editing, Visualization, Supervision, Project administration; Mengmeng Wang: Software, Resources.

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