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What is the impact of smart city development? Empirical evidence from a Smart City Impact Index

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A R T I C L E I N F O

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A B S T R A C T

Smart cities aim to provide benefits such as economic prosperity, environmental sustainability, and high quality of life to their citizens. However, we do not have a comprehensive understanding of how and to what extent these benefits are realized. This paper aims to find empirical evidence of both positive and negative results of smart city development. Smart City Impact Index is developed with indicators in four pillars of sustainability (economic, environmental, social, and governance) and technological dimension as technology is main driver of smart cities. The index was applied to South Korean cities, which are categorized as 1) first-wave smart cities that focus on transportation and security infrastructure, 2) second-wave smart cities that emphasize comprehensive urban management, and 3) non-smart cities. The index score was calculated for the years 2008 and 2018 to compare the before and after of smart city development. The results showed that the second-wave smart cities scored highest in both 2008 and 2018. However, the second-wave smart city had a lower score in both the environment and social dimensions. Smart city development in South Korea has had positive impacts on facilitating equality and citizen participation but negative impacts on people's perceptions of transparency and privacy.

1. Background

The smart city has gained a lot of attention in recent years because it promises benefits such as high quality of life, economic prosperity, and environmental sustainability through advanced technologies (Mosannenzadeh & Vettorato, 2014; Nam & Pardo, 2011a; Neirotti et al., 2014). Smart cities mainly emphasize information and communication technologies (ICT), but citizen participation, cooperation, and collaborative governance are also considered important contributors to successful smart city development (Yigitcanlar et al., 2018). There are many studies on smart city concepts and planning strategies (Aelenei et al., 2016; Alam & Porras, 2018; Kummitha & Crutzen, 2017) but not much information is available on the empirical results. Especially, there is a knowledge gap on to what extent the positive or negative impacts of smart city development are realized (Y Lim et al., 2019). Smart city projects involve a vast investment of financial, technological, human, and institutional capital and therefore, it is important to reflect on current smart city development to obtain a clear understanding of its impact and results.

Existing studies analyze the performance of cities and then rank them in the order of 'smartness.' Giffinger et al. (2007) developed indicators within six domains and evaluated European medium-size cities according to them. This model has been adopted and revised in other studies to develop a smart city framework or evaluation criteria (Battarra et al., 2015; Kola-Bezka et al., 2016). More recently, Bruni et al. (2017) and Shen et al. (2018) used this model to evaluate smart cities in Italy and China respectively. The indicators of these researches are anchored to predefined assets of cities. Moreover, there is little attention to the negative results stemming from smart city development.

This paper aims to provide empirical evidence of the smart city's contribution to urban sustainability by developing an index that measures both the positive and negative impacts of smart city projects. The main research question is: "How can we measure the impacts of a smart city and to what extent are those impacts realized?" This study takes South Korea as a case study. South Korea initiated smart city projects beginning in the mid-2000s, which makes it possible to evaluate their results.

The remainder of this article is as follows. The literature review provides an overview of the impacts of smart city development in economic, environmental, social, governance, and technological dimensions. Then indicators to measure the impact in each dimension are identified. The methodology section introduces the South Korean context, data collec-

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Table 1
Results of smart city development by sustainability domains and technology.

Dimensions	Positive results	Negative results
Economic	• Facilitating economic development	(not found in systematic review)
Environmental	• Environmental sustainability	(not found in systematic review)
Social	• Increasing quality of life • Enhancing equality • Empowering citizens	• Increasing polarization & inequality
Governance	• Enhancing citizen involvement • Transparent & democratic decision-making	• Reducing anonymity & democracy
Technological	• Fostering innovation • Increasing efficiency	• Privacy & technological security issues

Adopted and adjusted from (Lim et al., 2019).

tion, and index development. The analysis shows indexes in the years 2008 and 2018 in different city types to compare the results before and after the smart city development. It also includes detailed results on positive and negative impacts and robustness analysis. The discussion section summarizes the analysis and findings and finally, the conclusion section highlights the implication and limitations of this research and future research directions.

2. Multi-dimensional impacts of smart city development

2.1. Positive and negative impacts of smart city development by dimensions

Smart city development is often associated with sustainable development, which has four dimensions: economic, environmental, social, and governance. In addition, the technological dimension is included since technology is a major driver of the smart city (Yigitcanlar et al., 2018). Table 1 summarizes the positive and negative results of smart city development from a systematic literature review (Lim et al., 2019).

The most frequently mentioned positive impact of smart cities is economic development. Smart cities are expected to facilitate employment, new business opportunities (Kraus et al., 2015), and economic growth (Sarma & Sunny, 2017). It has been reported with EU smart city projects that the employment rate has increased (Batagan, 2011). This is partly because smart city project involves construction which generates jobs but also use of ICT infrastructures that enable active information and knowledge sharing (Angelidou, 2015; Gil-Garcia et al., 2016; Neirotti et al., 2014; Russo et al., 2016). With information, people can have a higher chance of finding jobs or starting new ventures (Schaffers et al., 2011; Wiig, 2015).

Environmental positive impacts include reducing energy consumption and CO2 emissions (Debnath et al., 2014; Mosannenzadeh et al., 2017; Snow et al., 2016). Passive design can be implemented to automatically reduce energy consumption in buildings (Zygiaris, 2013) and standards to encourage energy-efficient buildings can be implemented (e.g., the Green building standard (G-SEED) in Korea). Active measures such as sensing and monitoring energy use can initiate behavioural change in end users (Navarro et al., 2017). These measures in a smart city eventually contribute to the reduction in energy consumption and CO2 emissions (Hara et al., 2016). However, the negative impacts on economic and environmental dimensions are not explicitly discussed in the literature (Lim et al., 2019).

Increasing the quality of life is a major benefit of a smart city. It represents an increase in material and physical well-being (Yeh, 2017) or livability (Anthopoulos, 2017; Snow et al., 2016). Use of ICT can promote inclusiveness or reduce exclusion (Angelidou, 2015; Gil-Garcia et al., 2016; Zygiaris, 2013) and address inequality (Sajhau, 2017; Wiig, 2016; Yigitcanlar, 2015). However, polarization and inequality can be aggravated when technology is not equally distributed among citizens (Caragliu et al., 2011; Klimovsky et al., 2016; Neirotti et al., 2014; Rabari & Storper, 2014). Smart cities provide information on the job market and educational opportunities that support citizen empowerment (Angelidou, 2015; Ménascé et al., 2017; Wiig, 2016). Socially marginalized groups who have low education and skills as well as retirees can gain access to the job market through digital platforms such as Uber and Deliveroo (Ménascé et al., 2017).

Smart cities provide an environment where stakeholders can engage and collaborate via online participatory tools (de Wijs et al., 2016; Gil-Garcia et al., 2016; Romanelli, 2013; Schaffers et al., 2012). This can lead to transparent and democratic decision-making (de Wijs et al., 2016; Sajhau, 2017; Yigitcanlar, 2015). On the other hand, people may feel uncomfortable revealing their opinions when the possibility exists of exposing their identity (Galdon-Clavell, 2013), which may diminish freedom of speech and democracy (Elmaghraby & Losavio, 2014; Vanolo, 2016). Also, ICT infrastructures and platforms are provided by ICT vendors, whose systems monopolize the collection and management of urban data (including personal data) and thus may result in a democracy issue and danger of data misuse (Ben Letaifa, 2015; Hollands, 2008; Söderström et al., 2014).

Technology offers benefits in the form of innovations and investments (Afzalan et al., 2017; Bakici et al., 2013; Gil-Garcia et al., 2016; Kraus et al., 2015). Smart cities encourage the development of new technologies for better services (Nam & Pardo, 2011b). However, privacy and security issues are a major criticism of the technology-focused smart city because the smart city environment enables the gathering and sharing of sensitive personal information (Angelidou, 2017a, 2017b; Hollands, 2015).

2.2. Indicators to measure impacts of smart city development

Table 2 summarizes the variables and indicators. Within the economic dimension, economic growth is measured by GRDP per capita and local income tax per capita. Local income tax per capita reflects the average income level of the urban population. Within the environmental dimension, total electricity consumption per capita and renewable energy production and CO2 emissions per capita are used. There is no city-level data on total CO2 emissions but regional data on the industrial sector is available. The industrial sector makes up approximately 47% of total CO2 emissions in Korea. Within the social dimension, quality of life is measured by satisfaction with the urban environment (quality of air, water, land, noises, and green area), urban services (transportation, healthcare, education), and life in general. Citizen empowerment is measured by subjective socioeconomic status and employment of socially marginalized people. Subjective socioeconomic status represents the percentage of people who perceive their income level as falling into

Table 2
Operationalization of Smart City Impact Index.

Domain	Factor	Indicator	Source
Economy	Economic development	GRDP per capita (million KRW) Local income tax per capita (1000 KRW) Employment rate (%)	Lombardi et al. (2012); Kim, et al. (2016); Kourtit et al. (2012) Batagan (2011); Kraus et al. (2015); Hara et al. (2016); Kourtit et al. (2012)
Environment	Energy consumption reduction	Total electricity consumption per capita (MWh)	Lombardi et al. (2012); Mosannenzadeh et al. (2017); Hara et al. (2016)
	CO_2 emissions reduction	CO_2 emissions in the industrial sector (tonCO$_2$-eq)	Lombardi et al. (2012); Snow et al. (2016); Hara et al. (2016)
		Participating in environmental protection action (score)	Hara et al. (2016)
Social Dimension	Increasing quality of life	Average satisfaction with the environment (air, water, land, noise quality, and green space) (score)	Hara et al. (2016)
		Average satisfaction with one's living environment (score)	Hara et al. (2016); Yeh (2017)
		General satisfaction with life (score)	Anthopoulos (2017)
	Equality/ Inequality	Satisfaction with income (score) % of low-income group (%)	Hara et al. (2016) Hara et al. (2016)
	Citizen empowerment	Employment ratio of low-income (%) Employment ratio of elderly (%)	Wiig (2016)
Governance	Enhancing citizen involvement	% of population using online participatory tools (%) % of population participating in citizen initiatives (%)	Lombardi et al. (2012); Bakici et al. (2013); Gil-Garcia (2016)
	Transparent & democratic decision-making	People's perception of governmental transparency (score)	de Wijs et al. (2016)
		Perception of democracy (score)	de Wijs et al. (2016)
Technology	Fostering innovation	No. of patents (unit) % of R&D investment for ICT (%)	Lombardi et al. (2012); Hara et al. (2016) Batagan (2011)
	Knowledge-intensive industry	% of businesses in knowledge-intensive industry (%)	Tranos & Gertner (2012); Hara et al. (2016); Kourtit et al. (2012)
		% of employment in knowledge-intensive industry (%)	Lombardi et al. (2012); Kraus et al. (2015); Caragliu & Del Bo (2012)
	Privacy and security issues	Perception of information security (score)	Hara et al. (2016); de Wijs et al. (2016)

'low' among high, medium, and low earners. Socially marginalized people include the elderly (over age 65) and the low-educated who do not have a high school diploma. People with disabilities are excluded due to the lack of city-level data.

The governance dimension includes citizen involvement, transparency, and democracy. Citizen involvement is measured by the percentage of people using an online platform to express their opinion and the percentage of people participating in social initiatives. Transparency is represented by the overall perception of transparency within government agencies, and democracy represents the viewpoint of people toward general democracy. These data are only provided at the provincial level. Within the technological dimension, innovation is measured by the number of patents, which is provincial data. For city-level data, the number of patents is divided by the number of cities in the province. Innovation is also measured by the local government's budget for research and development (R&D). Indicators for the knowledge-intensive industry include the percentage of employment and businesses in the knowledge-intensive industry. Privacy issues are measured by asking people their subjective feelings about information security.

3. Methodology

3.1. Overview of smart city projects in South Korea and data collection

Informatization and digitalization in the early 2000s in South Korea enabled the adoption of ICT in urban development and management. The government has taken the lead in initiating several smart city initiatives since 2006. The first general plan was the U-Korea Plan (2006~2010) followed by U-City Plan (2009–2012) which is the foundation for 55 U-City projects in 45 cities (Lim et al. 2019). Here, 'U' is an abbreviation of ubiquitous, meaning fully accessible network in Korea. U-city was the former body of smart city, mainly focusing on ICT infrastructures including wireless sensor networks, surveillance cameras, internet networks, and public Wi-Fi to efficiently manage urban facilities. Since the smart city became a buzzword in the later 2000s, the Korean government also changed the official titles of plans and projects from 'U' city to 'smart' city.

According to the National Smart City Master Plans of the Ministry of Land, Infrastructure and Transport (MoLIT), smart city projects in Korea can be categorized into three phases shifting focus and characteristics: 1) U-cities (2008 ~ 2013), 2) the first wave smart cities (2014 ~ 2018), and 3) the second wave smart cities (2019 ~ 2023) (details of these plans and comparison can be found in Lim et al., 2023). Compared to U-cities, the first and second-wave smart cities are advanced models. In the government policy and planning documents, the major focus was shifted from ICT infrastructure to social infrastructure and governance pursued bottom-up initiatives and citizen participation (Park et al., 2018). The differences between the first-wave smart cities and the second-wave smart cities are in the mutuality of smart services. In the first-wave smart cities, the smart services were limited to transport and security based on sensor networks and surveillance cameras while in the second-wave smart cities, the services are expanded to the environment and administrations.

Table 3 provides a summary of the smart city projects initiated in Korea. Smart cities mostly began being developed around 2007/2008 and the average duration of a smart city is 12 years.

There are a total of 162 administrative cities in Korea. This figure includes Seoul, six metropolitan cities (Incheon, Busan, Daejeon, Daegu, Ulsan, and Gwangju), Sejong special autonomous city, Jeju special autonomous Island, and cities (Si & Gun) under eight provinces (Do). To observe the impact of smart city development, the projects started from 2015 onward are excluded. Sejong is also excluded because the city was newly initiated in 2012. A total of 73 projects were implemented in 52 administrative cities. The cities are categorized into three types: 1) first-wave smart city ($n = 41$), which are early-stage smart city projects that focus on transportation and security infrastructure; 2) second-wave

Table 3
Smart city projects in Korea.

Region	No.	Year	Duration	Smart services			
				T	S	E	A
Seoul	1	2011–2020	10	o	O	o	
Daegu	2	2006–2016	11	o	O		
Incheon	5	2008–2020	13	o	O	o	
Daejeon	1	2003–2012	10	o	O		
Ulsan	2	2007–2018	12	o	O	o	
Sejong	1	2006–2030	25	o	O	o	
Gyeonggi	44	2008–2018	11	o	O	o	o
Gangwon	1	2007–2017	11	o	O		
Chungbuk	3	2008–2018	12	o	O		
Chungnam	4	2004–2018	15	o	O	o	
Jeonbuk	4	2006–2019	13	o	O	o	
Jeonnam	1	2007–2015	9	o	O		
Gyeongbuk	1	2007–2015	9	o	O		
Gyeongnam	3	2007–2019	12	o	O	o	
Sum/Average	73	2007–2018	11	–			

T: Transportation, S: Security & Safety, E: Environment, A: Administration.
Source: http://www.lh.or.kr/contents/cont.do?sCode=user&mPid=175&mId=177&menuYear=.

smart city ($n = 11$) that provide comprehensive urban services including transportation, facility management, security and disaster management, healthcare and welfare, public administration, and environment management; and 3) non-smart city ($n = 108$).

The data is collected at two points in time: 2008 when the smart city projects were initiated and 2018 as the present timeline. Depending on data availability, the year varies from 2008 to 2011 and 2015 to 2018. The method is to compare the index in the years 2008 and 2018 so that the impact of smart city development can be shown clearly. Most of the data were collected from the Korea Statistics Information System (KOSIS).

The data were standardized with a z-score so that all indicators have the same unit of measurement and were converted to a percentile, ranging from 0% to 100% for intuitive interpretation. The score shows the relative position of each city. For example, 0% in GRDP per capita in a city does not mean the actual GRDP per capita is 0 in that city. Rather, it means the city has the lowest GRDP per capita compared to the other cities. Some of the indicators were reversed to give a higher score, thus representing better performance. For example, a lower percentile in total electricity consumption per capita is desirable. So, the standardized score is deducted from 100 to give a higher score to cities where electricity consumption per capita is less. This goes the same with CO2 emissions and the percentage of people who perceive their income level as low.

3.2. Smart City Impact Index

The Smart City Impact Index was developed based on the theoretical framework in Section 2, having indicators as outlined in Table 3. Cronbach's alpha test was carried out for each dimension to check the internal consistency of the data. For the economic dimension, GRDP per capita and local income tax per capita showed the highest standard alpha, 0.81 for 2008 and 0.84 for 2018 data. The environmental dimension showed a low value due to an imperfect dataset. The highest combination was the one that excluded renewable energy production (0.12 in 2008 and 0.53 in 2018). Social variables had the highest standard alpha 0.68 in 2008 and 0.64 in 2018 data with life satisfaction, perception of income level, and employment rate of the low-educated and elderly. When including all four governance variables, the standard alpha was 0.61 for 2008 data and 0.73 for 2018 data. Finally, all the technological variables except the percentage of the R&D budget showed a standard alpha of 0.67 and 0.80 for 2008 and 2018 data respectively. Fig. 1 shows the chosen indicators for each dimension and the equation used to compute the Smart City Impact Index. The indicators were accumulated with an equal weight scheme. Each dimension has the same weight because each dimension has the same importance on sustainability, and the variables in each dimension also assume equal weight.

4. Analysis

4.1. Smart City Impact Index by city type in 2008 and 2018

The total average of the smart city impact index was 48.8 in 2008 and showed a slight increase in 2018 by 0.2 percent. Second-wave smart cities scored highest in both years while the first-wave smart city showed a decrease of 0.1 percent. Non-smart cities scored the lowest (see Table 4). Some indicators showed an already-existing gap between non-smart cities and smart cities in 2008. Second-wave smart cities already had a higher GRDP per capita and local income tax per capita. These include Asan, Hwaseong, and Seoul, where the population and businesses are densely situated. In the environmental dimension, CO2 emissions in the industrial sector and participation in environmental protection were high in first- and second-wave smart cities than in non-smart cities. Perceptions of the government's transparency and general democracy were higher in second- and first-wave smart cities than in non-smart cities. Finally, there was a gap in the technological dimension as the number of patents, businesses, and employment in knowledge-intensive industries was higher in second- and first-wave smart cities than in non-smart cities. On the other hand, non-smart cities scored highest in citizen initiatives and on all four social indicators.

Second-wave smart cities showed the highest index score in 2008 and 2018. By each indicator, GRDP per capita, local income tax per capita, CO2 emissions in the industrial sector, environmental protection behavior, online participation, transparency and democracy, and the number of patents, businesses, and employment in knowledge-intensive industries remained the highest in both years. Electricity consumption per capita, general satisfaction with life, and perception of economic status became the highest indicators in 2018. Non-smart cities had the lowest index score in both years. However, some of the indicators remained highest among city types in 2018, including empowerment of the low-educated and elderly as well as perception of information security. First-wave smart cities showed a higher index score than non-smart cities but scored lower than second-wave smart cities.

The descriptive analysis showed that there is a difference among city types. One-way ANOVA was performed to check whether this difference in mean was statistically significant. Two assumptions of one-way ANOVA were checked using Shapiro's test for normal distribution and Levene's test for homogeneity in variance. According to Shapiro's test, Smart City Impact Index

Dimensions	Cronbach's alpha Y08	Cronbach's alpha Y18	Variables		Indicators
Economy	0.81	0.84	Economic growth	C1	GRDP per capita
				C2	Local income tax per capita
Environment	0.12	0.53	Environmental Sustainability	E1	Electricity consumption per capita
				E2	CO2 emission
				E3	Participation in environmental protection
Social	0.68	0.64	Quality of life	S1	General satisfaction on life
			Equality/inequality	S2	Perception on economic status
			Citizen empowerment	S3	Employment rate of low-educated
				S4	Employment rate of elderly (65+)
Governance	0.61	0.73	Citizen involvement	G1	Participation via online participatory tool
				G2	Citizen initiatives
			Transparency & democracy	G3	Perception on government's transparency
				G4	Perception on general democracy
Technology	0.67	0.81	Innovation	T1	Patents
			Knowledge intensive industries	T2	Businesses in knowledge intensive industries
				T3	Employment in knowledge intensive industries
			Privacy	T4	Perception on information security

$$SCII = \frac{1}{5}\{\frac{1}{2}(C1 + C2) + \frac{1}{3}(E1 + E2 + E3) + \frac{1}{3}\left(S1 + S2 + \frac{1}{2}(S3 + S4)\right) + \frac{1}{2}\left(\frac{1}{2}(G1 + G2) + \frac{1}{2}(G3 + G4)\right) + \frac{1}{3}\left(T1 + \frac{1}{2}(T2 + T3) + T4\right)\}$$

Fig. 1. Smart City Impact Index.

Table 4
Average scores of Smart City Impact Index.

Dimensions	Indicators	2008 NS	2008 SC1	2008 SC2	2008 Mean	2018 NS	2018 SC1	2018 SC2	2018 Mean
Smart City Impact Index	47.4	50.6	56.1	48.8	47.4	50.5	58.2	49.0	
Economy	GRDP per capita	44.1	45.0	60.1	45.5	44.7	46.3	56.6	45.9
	Local income tax per capita	39.2	54.8	72.8	45.5	38.5	56.1	76.1	45.6
Environment	Electricity consumption	54.5	54.9	51.2	54.4	54.2	56.1	56.9	54.9
	CO2 emissions in industrial sector	44.3	58.3	63.7	49.2	44.3	63.8	66.6	50.8
	Environmental protection behavior	47.0	58.7	75.4	51.9	46.8	58.1	79.6	51.9
Social	Satisfaction with life	51.1	41.7	29.1	47.2	49.3	45.6	49.6	48.3
	Perception of income level	52.6	47.2	47.3	50.8	39.9	58.5	75.7	47.1
	Employment of low-educated	58.8	40.0	20.6	51.4	63.1	27.9	15.3	50.8
	Employment of elderly	58.8	38.6	19.5	50.9	60.5	39.9	18.0	52.3
Governance	Online participation	49.3	45.7	55.5	48.8	50.1	48.3	52.9	49.8
	Citizen initiatives	52.2	43.0	33.6	48.6	49.7	55.8	55.2	51.6
	Perception of transparency	42.4	58.0	79.8	48.9	45.6	46.7	55.1	46.6
	Perception of democracy	47.1	59.1	75.9	52.2	49.2	49.9	74.1	51.1
Technology	No. of patents	44.9	49.1	61.7	47.2	44.7	49.5	62.0	47.1
	Businesses in knowledge-intensive industries	37.7	66.8	80.8	48.2	36.2	67.4	82.6	47.4
	Employment in knowledge-intensive industries	36.9	62.3	88.3	46.9	37.2	61.1	88.8	46.9
	Perception of information security	47.0	41.1	30.4	44.3	57.8	30.1	14.9	47.7

all the city types in 2008 and 2018 were normally distributed. Levene's test also showed that all city types in both years were homogeneous in their variance. Since the two assumptions were met, one-way ANOVA was performed. The results for 2008 and 2018 showed a statistically significant difference among city types (p-value = 3.86e–07 for 2008 and 1.09e–08 for 2018). To check which pair of city types showed a difference, post hoc testing was performed using Tukey multiple comparisons of means. The result of 2008 showed that the second-wave smart cities were significantly different from non-smart cities (p-value lower than 0.001) and in 2018 they were significantly different from both first-wave smart cities and non-smart cities (see Table 5).

4.2. *Positive and negative impacts*

Table 6 shows the distinction between positive and negative impacts for each indicator. Deducting each indicator's score in 2008 from its score in 2018 shows the change. An increase in the score represents positive change while a decrease means negative change. Some of the indicators show either a positive or negative impact depending on the change, as marked in column 2. P means positive impact while N means negative impact. Some of the indicators measure both positive and negative impacts and are marked 'P/N'. For example, the perception of economic status measures equality or inequality. When the score is de-

Table 5
Statistics of one-way ANOVA and Tukey multiple comparisons.

One-way ANOVA					
Year	Df	Sum sq.	Mean sq.	F value	*p*-value
2008	2	932	466.1	16.25	3.86e-07***
2018	2	1289	644.4	20.66	1.09e-08***

Tukey multiple comparisons of means (for 2008)				
	Diff	Lwr	Upr	P adj
SC1-NS	3.188	0.863	5.513	0.004**
SC2-NS	8.720	4.709	12.731	0.000***
SC2-SC1	5.532	1.223	9.835	0.007**

Tukey multiple comparisons of means (for 2018)				
	Diff	Lwr	Upr	P adj
SC1-NS	3.050	0.625	5.474	0.009**
SC2-NS	10.781	6.599	14.963	0.000***
SC2-SC1	7.731	3.244	12.218	0.000***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

creased, it means there are more people who consider themselves low-income. Thus, equality is decreased or inequality is increased, either showing a negative impact. The following columns, 3 to 6, show the difference between the 2008 score and the 2018 score for each city type and the average of all cities. Marked with dark gray are the negative impacts while light gray represents the positive impacts.

Evidence of positive impacts are indicators where the scores of both first- and second-wave smart cities increased. Local income tax per capita reflects an increase in a city's income. First-wave smart cities increased by 1.26 while second-wave smart cities increased by 3.32. Non-smart cities decreased by 0.70. This tendency shows that smart city development positively influenced the income level within the city, especially for second-wave smart cities. The score for electricity consumption per capita increased also in both first- and second-wave smart cities, which means less energy was consumed. CO2 emissions in the industrial sector also showed an increase in all three city types, but first-wave smart cities increased the most (5.57) followed by second-wave smart cities (2.88) and non-smart cities (0.03). Satisfaction with life, perception of income level, and citizen initiatives showed an increase, wherein second-wave smart cities showed a greater increase than first-wave smart cities. The number of patents and businesses in knowledge-intensive industries showed a slight increase in both first- and second-wave smart cities.

The negative impacts are those indicators where both first- and second-wave smart cities decreased. The employment rate of low-educated decreased in both first- and second-wave smart cities while non-smart cities showed an increase. Perception of the government's transparency and democracy decreased. In particular, the transparency of the government decreased more in second-wave smart cities than in first-wave smart cities. Democracy decreased more in first-wave smart cities (–9.26) than in second-wave smart cities (–1.85). Finally, in the technology dimension, the perception of information security decreased. This tendency indicates that smart city development can cause more concerns with respect to information security.

Some of the indicators showed different results in first- and second-wave smart cities. GRDP per capita, the employment rate of the elderly, and online citizen participation increased in first-wave smart cities but decreased in second-wave smart cities. A decrease in the employment rate of the elderly in second-wave smart cities may reflect that comprehensive smart city development negatively influenced the older generation. Online citizen participation decreased in only second-wave smart cities; however, its absolute score remained the highest. This means the gap between the city types was reduced. On the other hand, participation in environmental protection behavior and employment rate in knowledge-intensive industries decreased in first-wave smart cities and increased in second-wave smart cities. This may reflect the limitation of first-wave smart cities only implementing "hard" infrastructure rather than "soft" solutions such as economic strategy (Neirotti et al., 2014). GRDP per capita increased in first-wave smart cities but decreased in second-wave smart cities. Implementing "hard" infrastructure boosted the effect on the economy but investing in comprehensive and 'soft' measures did not yield an immediate return.

To check whether the difference in scores showed statistical significance, we performed simple linear regression using the difference in differences for each indicator. In this regression, we paired non-smart cities with second-wave smart cities and first-wave smart cities and second-wave smart cities (see Table 6). The difference in differences was useful in measuring the impact of policy by analyzing the changes that occurred over time within the groups and the difference between the treatment group (in this case first- and second-wave smart cities) and the control group (non-smart cities) (Gertler et al., 2016). The difference in differences analysis assumes the treatment group would have an equal trend with the control group when there was no treatment. A simple linear regression model was created by pairing first-wave smart cities with non-smart cities and second-wave smart cities with non-smart cities.

The result of the first-wave smart city and non-smart city pairing showed that perception of income level, employment of low-educated, citizen initiatives, perception of government's transparency, and perception of information security had statistically significant values (p-value £ 0.05). The result of the second-wave smart city and non-smart city pairing showed a significant difference in perception of income level, citizen initiatives, perception of transparency, and information security.

4.3. Robustness analysis

For robustness analysis, we first used min-max normalization instead of z-score and percentile. The result showed that second-wave smart cities still scored the highest in both 2008 and 2018. The difference was initially only that first-wave smart cities showed a decrease in index score but a min-max normalized score and that only the second-wave smart cities showed an increase. Also, the changes from 2008 to 2018 showed somewhat different results. Initial analysis indicated that both first- and second-wave smart cities were better than non-smart cities in most of the indicators. However, the adjusted score showed that second-wave smart cities performed especially better than non- or first-wave smart cities. With min-max normalization, the distinction between first- and second-wave smart cities becomes clearer.

Due to the lack of city-level data, some indicators used provincial-level data. These indicators include CO2 emissions in the industrial sector, participation in environmental protection behavior, employment ratio of the elderly, all four governance indicators, and the number of patents. These indicators were removed, and the index was recalculated. Even after removing these indicators, second-wave smart cities still scored the highest and showed the greatest increase from 2008 to 2018. The robustness analysis ensures the general tendency of each city category remains similar.

4.4. Discussion of results

The findings can be summarized as follows. First, the mean of second-wave smart cities' index scores was the highest among city types in 2008 and 2018, followed by first-wave smart cities and non-smart cities. While the average index score showed a slight increase from 48.8 in 2008 to 49.0 in 2018, second-wave smart cities showed an increase from 56.1 to 58.2. Second-wave smart cities excelled in most of the indicators except for employment of the low-educated and elderly, citizen initiatives, and perception of information security. Non-smart cities scored highest in those indicators except for citizen initiative, where first-wave smart cities scored the highest. This result implies that smart

Table 6
Identifying the positive and negative impact.

Dimensions	Index	P/N	Difference (2018 – 2008)				DD regression p-value	
			NS	SC1	SC2	Average	NS vs. SC1	NS vs. SC2
Smart city impact index		–	0.04	–0.10	2.10	0.14	0.922	0.395
Economy	GRDP per capita	P	0.54	1.33	–3.45	0.47	0.899	0.693
	Local income tax per capita	P	–0.70	1.26	3.32	0.08	0.741	0.693
Environment	Electricity consumption	P/N	–0.30	1.20	5.63	0.49	0.791	0.549
	CO2 emissions in the industrial sector	P/N	0.03	5.57	2.88	1.64	0.457	0.729
	Environmental protection behavior	P	–0.20	–0.54	4.15	0.01	0.964	0.339
Social	Satisfaction of life	P	–1.86	3.86	20.52	1.15	0.461	0.100
	Perception of income level	P/N	–12.71	11.27	28.44	–3.74	0.0006***	0.0004***
	Employment of low-educated	P/N	4.24	–12.13	–5.39	-0.62	0.021*	0.422
	Employment of elderly	P/N	1.68	1.36	–1.48	1.38	0.965	0.789
Governance	Online participation	P/N	0.78	2.53	–2.55	1.00	0.819	0.802
	Citizen initiatives	P	–2.58	12.82	21.59	3.03	0.031*	0.048*
	Perception of transparency	P/N	3.27	–11.23	–24.61	–2.36	0.0589.	0.032*
	Perception of democracy	P/N	2.12	–9.26	–1.85	–1.07	0.144	0.763
Technology	No. of patents	P	–0.20	0.32	0.31	–0.03	0.697	0.856
	Businesses in knowledge-intensive industries	P	–1.50	0.58	1.78	–0.74	0.732	0.750
	Employment in knowledge- intensive industries	P	0.30	–1.15	0.45	–0.06	0.806	0.989
	Perception of information security	N	10.83	–11.03	–15.46	3.42	0.001**	0.024*

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

city development in Korea generates desirable results compared to non-smart cities. A smart city provides a pleasant living environment with high accessibility to information, a connected and inclusive environment (Angelidou, 2015; Gil-Garcia et al., 2016; Wiig, 2015) and help in boosting the economy, quality of life, and innovation.

Secondly, the mean of the two types of cities showed strong significance between second-wave smart cities and non-smart cities in 2008. The difference between first-wave smart cities and non-smart cities and between second- and first-wave smart cities showed a weaker significance. On the other hand, in 2018, the mean index score showed a significant difference between second-wave smart cities and non-smart cities and between second- and first-wave smart cities. Smart city development assisted in the attainment of a higher score for second-wave smart cities, especially in electricity consumption per capita, satisfaction with life, equality (perception of income level), and citizen initiatives. These indicators were lower than the average in 2008 but ranked higher than the other city types in 2018. However, first-wave smart cities performed lower than second-wave smart cities. This tendency indicates that first-wave smart cities that focus on infrastructure implementation have less difference from non-smart cities in performance. For example, In the

Gyeonggi region, the difference between non-smart cities and first-wave smart cities is narrow since the region is mostly an urbanized area. Even the non-smart cities benefit from wider ICT infrastructures in the region. On the other hand, first-wave smart cities in rural areas such as Chungnam (e.g., Boryeong, Gyeryong) are less different from non-smart cities (e.g., Taean, Buyeo) in terms of infrastructure and smart services. First-wave smart cities implemented transportation and security services that can ease the everyday life of citizens, but they did extend into the realm of greater impact (e.g., quality of life and citizen empowerment or involvement). For smart city development to be successful, equipping citizens with technology is not enough. Policy and community involvement are also needed to realize positive impacts while avoiding the negative ones (Yigitcanlar et al., 2018).

The third finding is that there is a pre-existing gap between non-smart cities and smart cities. Second-wave smart cities have better economic assets (GRPD per capita and local income tax per capita), have a better perception of transparency and democracy, and have the seeds for innovation (i.e., patents and knowledge-intensive industries). This initial gap may influence the change that transpired over the 10-year period, wherein satisfaction with life and perception of income level became highest in second-wave smart cities. On the other hand, indicators that are not directly related to smart city development remained at a similar position. In 2008, non-smart cities performed better on satisfaction with life, perception of income level, employment of the low-educated and elderly, citizen initiatives, and perception of information security. Ten years later, employment of the low-educated and elderly and the perception of information security were still the highest indicators in non-smart cities. Comprehensive smart city development is needed to yield better results in the environmental and social dimensions. As mentioned in Section 4.1, the second-wave smart cities were already 'doing well' in terms of social and economic conditions. For example, representative second-wave smart cities such as Seoul and Incheon are all located in metropolitan areas, where the population and businesses are densely located and have abundant amenities. Adding smart city investments in such cities can increase the already existing gaps between smart cities and non-smart cities. However, smart cities require basic prerequisites such as advanced ICT infrastructure to fully exploit smart services, so it was a logical choice to invest in those cities.

The final finding is that there was statistically significant evidence of both positive and negative impacts. Two positive and three negative impacts are statistically significant according to the difference in differences regression. Perception of income level and citizen initiatives were better in smart cities while employment of the low-educated, transparency and privacy were worse in smart cities. First- and second-wave smart cities had an increased score in the perception of income level and citizen initiatives. This tendency implies that smart city development can contribute to lowering the gap between the rich and poor and can support any form of citizen participation in social activities. On the other hand, employment of the low-educated, perception of the government's transparency, and privacy were decreased in both first- and second-wave smart cities. Although second-wave smart cities' transparency score remained the highest among city types, the overall score decreased by 24.61 percent. This tendency reflects a smart city's ability to negatively influence people's view of the government.

5. Conclusion

There is missing empirical evidence on the impacts of smart cities. Moreover, the literature on smart cities mostly emphasizes the potential positive impacts rather than the negative ones (Lim et al., 2019). In this study, we pay attention to this knowledge gap in the research on smart cities. By providing comprehensive evaluation framework, we analyzed two phases of smart cities and showed empirical evidence of smart city development's impact on urban sustainability. Our study has some limitations. First, the analysis is based on an existing dataset from KOSIS. Some data was not available on a city level and provincial data was used, which may not directly reflect smart city development on the city's sustainability. Second, the distinction between smart and non-smart cities is based on the government's projects, which may not include citizen-initiated smart city projects. Third, the geographical scope is limited to Korea. Further studies can explore other countries and even compare international results.

Despite these limitations, this study arrives at some meaningful insights and conclusions. Based on the results discussed in section 4, the first main conclusion is that smart cities do indeed have positive impacts across various dimensions. Smart city development in Korea does, in fact, contribute to economic development, energy consumption reduction, quality of life, equality, citizen initiative, and innovation. We have found a direct relationship between smart city development and (relative) higher performance in all sustainability dimensions and in the technology dimension. In Korea, second-wave smart cities performed better than the other city types and showed an increase over time. Second-wave smart cities have a more advanced program than first-wave smart cities, which focus only on implementing "hard" infrastructure. In smart cities, implementing "hard" infrastructure is not enough (Hollands, 2008). What really makes the difference is a "soft" domain that includes policies or strategies for economic development, social inclusion and innovation (Neirotti et al., 2014).

The second main conclusion is that smart city development also entails negative impacts. The negative impacts of smart city development has been relatively less highlighted in the literature (Lim, et al., 2019). However, the empirical analysis showed that negative impacts occur on citizen empowerment, transparency, and privacy. People feel more concerned about the government's transparency and information security in smart cities. There is a need for more attention to be paid to citizen empowerment and information security in smart city development. An increase in accessibility to information may increase job opportunities for socially marginalized groups (Ménascé et al., 2017). It turns out, however, that a greater gap can be created without proper digital education on how to properly use technology.

Smart city policies need to focus more on how the ICT infrastructure benefits citizens and increases their quality of life. Especially, the focus needs to turn to the socially marginalized people (e.g., digital illiterates), and how to include them in benefitting from smart services. For example, Seoul initiated the '2022 Seoul Digital Capacity Building Training Plan' including public training services for the elderly. Trainers visit parks or where the elderly frequently visit to have a one-on-one training session with them about how to use smart phones and smart services. The smart cities that have an aging population can follow the example of Seoul, to provide an equal chance to benefit from smart city projects to all citizens.

This study provides empirical results on the impacts of smart city development which have not been thoroughly studied. However, more (systematic) research is needed to provide more solid evidence. We need more large N studies to get greater overall insights into the impacts of smart cities. In addition, there is a need for in-depth and comparative case studies to investigate the performances in each dimension and these studies need to take contextual factors into account. All in all, a smart city is more than just technology implementation (Hollands, 2008). Community and policy environments also pave the way for successfully developing smart cities (Hollands, 2008; Yigitcanlar et al., 2018). Perhaps this is not explicitly shown in the Korean context where the government is largely in charge of smart city development. Instead of a government-led, top-down prescribed strategy, localized strategies are needed since the cities have different assets.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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