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Smart cities and the urban digital divide

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The debate on urban smartness as an instrument for managing more efficient cities has been revolving around the notion that Smart Cities might be causing an increase in inequalities. This effect would be caused by the role played in smart urban transformations by Multi-National Corporations, which would be influencing local policymakers' agendas. In this work we empirically verify whether smart urban characteristics are associated with an increase in urban inequalities along the digital divide dimension among urban dwellers. To this aim, we exploit a large database of 181 European cities, with data on smart urban characteristics, along with measures of the digital divide obtained with the use of survey data carried out at the European Union level. Results show a negative causal relation between the level of urban smartness and the digital divide within-EU cities. Our findings are robust to a number of robustness checks.

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INTRODUCTION

The debate on urban smartness as an instrument for planning and managing more efficient cities has been recently positing that Smart Cities could be raising inequalities. This effect would be due to the role of driver of smart urban transformations played by multinational corporations, which, in a dystopic view, would influence local policymakers' agendas[1,2]. For instance, ref. [3] argues that relevant investment to counterbalance technological tendencies to favor the wealthy and connected will be required, lest the Smart City paradigm broadens pre-existing inequalities. This concern is gaining attention in the research arena. For instance, the literature review presented in ref. [4] highlights the emergence of a niche branch of scientific works dealing with smart inclusive cities—cities that combine investment in digital technologies with an equitable distribution of the benefits stemming from the latter.

Ever since the emergence of digital technologies in the early 1990s, the literature has discussed the potential pitfalls of an uneven distribution of e-skills under the umbrella of the *digital divide*. According to ref. [5], "*Lloyd Morrisett coined the term digital divide to mean "a discrepancy in access to technology resources between socioeconomic groups" (Robyler, 2003, p. 191)*".

Despite this term being around for about three decades, statistics and stylized facts suggest that the extent of the digital divide has far from disappeared. For instance, according to EUROSTAT statistics, in 2021 about 90 percent of people living in Zeeland, a NUTS2 region in the Netherlands, had ordered at least once in their life goods or services over the internet for private use, against a minimum EU27 of 15 percent (in the region of Yugoiztochen, in Bulgaria). In the same year, while basically, all (99 percent) interviewees in the NUTS2 region of Northern and Western Ireland declared using the internet at least once a week, the same statistic drops to two-thirds of the sample in the Bulgarian region of Severozapaden. While over time these territorial divides are converging, they can still significantly affect the potential positive impact of the diffusion of digital technologies.

Over the past 3 years, the digital divide has been made dramatically apparent by the COVID-19 pandemic outbreak. When, during the first waves of full lockdowns enacted in most Countries, tertiary and schooling activities were moved online, many economic outcomes showed significant worsening. Among these, learning outcomes in pupils (as documented in ref. [6], who find that "Middle-class families were able to maintain higher standards of education quality in a critical context, while children from socially disadvantaged families had few learning opportunities both in terms of time and learning experiences, schoolwork and maintenance of after-school activities", p. 635), and service sectors' productivity[7]. In ref. [7], effects only include the direct impact of COVID-19-induced lockdowns through the channel of the uneven distribution of digital technologies.

In this paper, we combine the issues of the inequality-enhancing role of Smart Cities on the one hand, and the digital divide, on the other, which have hitherto remained unexplored.

Related research discusses additional dimensions of inequality, both within the Smart City framework (e.g., ref. [8], discussing the negative impact of urban smartness on income inequality), as well as outside of this branch. For instance, ref. [9] shows that low-income brackets within populations, and minorities, in countries characterized by different institutional economic contexts such as UAE, Mexico, and Northern Ireland are exposed to greater risk of energy poverty and access to intra-urban transport; along the same lines, ref. [10] documents substantial urban-rural differences in quality of life, with a particularly relevant divide characterizing within-cities inequalities.

In fact, empirical work on the relation between urban smartness and inequalities is surprisingly scant. Previous studies found that a negative relationship exists between urban smartness and the intensity of urban income inequalities, suggesting that Smart City features, if anything, help reduce income inequalities[8]. Moreover, despite the persisting relevance of the digital divide in Europe, the Smart City literature is still lacking a sound empirical assessment of the role of a digital divide in enhancing, or hampering, the impact of urban smartness.

In this work, we empirically verify whether smart urban characteristics are associated with an increase in urban inequalities along the digital divide dimension among urban dwellers. Our aim is therefore to bring together the strands of literature summarized above by asking the following research question:

RQ: Is urban smartness associated with a higher digital divide?

In order to provide an empirical test of this hypothesis we exploit a large database of 181 European cities, with data on smart

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urban characteristics, along with measures of the digital divide obtained with the use of EU-level survey data. Our results suggest that a negative association exists between the level of urban smartness and the intensity of the (within-city) digital divide. Results are robust to a number of consistency checks.

In our empirical model, the digital divide within each city is the dependent variable, while an indicator summarizing a city's level of smart characteristics is the independent variable of interest, along with a set of control variables.

The digital divide is measured by different indicators, obtained by using individual-level data. The probability of owning and using different digital devices (mobile phones, desktops, laptops, and tablets) is obtained by a logistical model, with right-hand-side variables including relevant individual-level determinants such as age, gender, education, employment, and country of residence. The residual from these regressions, representing the unexplained variance of the individual-level digital divide, is aggregated at the city level to obtain a general measure of within-city digital divide, and then combined to obtain ownership and use measures, subsequently used as dependent variables in our empirical model. Aggregation of individual indicators at the urban level is obtained by calculating the standard deviation of individual responses for either the combined group of questions related to ownership and usage, or the separate indicators, respectively (see Section 5 for additional details).

The smartness indicator instead is a summary measure, at the city level, obtained by aggregating data on the six axes of our preferred Smart City definition, i.e. human capital, social capital, transport infrastructure, ICTs, natural resources, and e-government. Specifically, the six axes of the definition of a Smart City have been measured with Urban Audit data via a principal components analysis (henceforth, PCA) approach. Multiple indicators for each axis have been reduced first to a single principal component, then aggregated to obtain a single principal component measuring overall urban smartness by calculating unweighted averages of the individual PCs.

The rest of the paper proceeds as follows. We first critically review (Subsection 1.2) prior work on the digital divide, focusing on both its definition and its determinants, and then link this strand to the Smart City literature. Section "Results" presents both baseline estimates, as well as a number of robustness checks, run to narrow down the scope of our empirical answer. Section "Methods" introduces the empirical methodology and the data set, constructed to answer our research question. Section "Discussion" discusses and concludes.

Literature review

Do Smart Cities cause the digital divide? The scientific debate on the extent of the digital divide dates back to the period when Information and Communication Technologies (henceforth, ICTs) first diffused in developed Countries, after the development of the World Wide Web[9]. Specifically, the term was first proposed in the mid-'90s by Lloyd Morrisett, as Chair of the Markle Foundation[11].

While this was traditionally dealt with as a question of having or not having access to ICTs, more recently the literature has suggested that three layers may exist underneath this concept[12,13]:

- first-order digital divide (ICT access or connectivity);
- second-order digital divide (ICT use or capability);
- third-order digital divide (ICT outcomes/returns or content).

Recent research has focused on examining the determinants of the second and third level[14–16] of the divide as the first level, focused on access has, in part, lost significance with the increase in the diffusion of broadband and wireless connections. For instance, ref. [17] reports that, based on survey data, 97% of European households have a broadband internet connection at home, while this figure drops to 65% in 2015 for American households, as reported by ref. [18]. When considering infrastructure, the interrelation between fixed and mobile providers is crucial, with the growing importance of mobile coverage that might help overcome physical obstacles to fixed telecommunication infrastructure, especially in rural and remote areas[19].

However, as a cautionary note on considering the first-order divide now irrelevant, ref. [20] warns that the definition of the first-level digital divide has to be extended to include material access. The authors highlight how material access, in terms of the means required to maintain the use of the Internet over time (including the expenses related to the devices used to connect to the web, the software, and subscriptions) are still a relevant obstacle to access to the relevant contents of the Web for portions of the population.

The debate so far presented is associated with the contrasting role played by absolute ownership disparities (across Countries, territories, industries, gender, and profession) and relative usage intensity as evidenced in applied studies. The literature has now found a consensus about the stronger effect caused by the latter with respect to the former[21]. This seems to be a particularly relevant discrepancy for institutional settings in the early stage of the development process[22].

The effects and impact of the digital divide have been particularly relevant in the recent COVID-19 pandemic, where the movement of various activities from in-person to online has further widened the gap between individuals and households with good and stable internet access, mainly located in urban areas in developed countries, and the others. The negative implications of this disparity are relevant for work activities, education, access to health, and social connections[23,24].

As for the determinants of this issue, much research has been devoted to the identification of the factors driving the intensity of the digital divide, disentangling the different roles played by individual factors from more aggregate, structural ones. In ref. [25], these determinants are summarized as follows:

> "*Three categories of findings are discussed:* (1)) *Economic and technological determinants relating to prosperity and modernity. For example: income levels, electricity and telecommunication infrastructure.* (2) *Institutional determinants relating to the political system and the rule of law. For example: regional regulations and societal arrangements.* (3) *Social determinants focussing on people-based processes. For example: demographics and education levels*"[25], (p. 337).

Based on data from official data sources for eight countries (US, UK, Germany, Italy, Japan, Korea, China, and Mexico) between 1995 and 2003[26], highlight the importance, as determinants of the country-level digital divide, especially of educational attainment levels, gender, and life stage variables, with younger individuals more likely to have access and exploit the Internet. They also show how people living in affluent regions register an advantage in access, a result that has been further explored and linked to differences in individual characteristics that are unequally distributed between urban and rural areas and between rich and less-developed regions[27,28]. Among the relevant factors at the geographic level that might influence the extent of the digital divide[14], stress the importance of differences in the physical structure of broadband networks, implicitly providing an advantage for well-connected urban areas[12] examine the link between the digital divide and the urban ranking distribution and find that cities that rank high have lower levels of first and second level digital divide among their inhabitants, corroborating the importance of the urban-rural divide. More specifically dealing with the role of cities and urban density, ref. [29] suggests that "*access to [IC] technologies is easier and cheaper in cities (than in rural areas) because they have better telecommunications infrastructure, and the* *costs of the deployment of new infrastructure are lower. Besides, cities tend to concentrate on high-skilled labor and knowledge resources (…). Likewise, faster network connections are available in highly populated areas compared to low-density territories*"[29], (p. 223). Ref. [30], considering country-level data as well, suggests, along with the above-mentioned determinants, the importance of telecommunication (TLC) pricing measures, regulatory quality, and infrastructure endowment indicators. Ref. [31] uses US state-level data and provide validation for additional determinants, in terms of relevant individual characteristics, of the digital divide which include social capital, openness, and ethnicity[32], using individual-level data for technology adoption in the EU, single out the importance of educational levels as an important driver of digital divide. Ref. [33] provides an overview, by means of a thorough literature review, of the determinants of the digital divide and confirm the importance of age, gender, socioeconomic status, ethnicity, and geography.

A relevant stream of studies has in fact investigated the extent of the divide between urban and rural areas, highlighting the role of physical impediments to TLC infrastructure (fast broadband connections that are, more difficult to install in remote, rural areas) and the role of other differences between rural and urban inhabitants[29,34]. Digital divide as measured by bandwidth is positively related to income[35], which is of itself unequally distributed across space and research has highlighted the emergence of an increasing digital divide also among other categories of vulnerable groups, represented by citizens with lower educational levels, cognitive disabilities and the elderly[36], all of which are more likely concentrated in disadvantaged areas[37–39].

It is also worth looking at how research on the digital divide relates to the burgeoning literature on Smart Cities. The aim here is not to provide a comprehensive review of the various definitions that this concept has attracted over the past decade; instead, it is here important to stress that, among many, our work draws upon a highly cited definition[40]. In this case, cities are identified as smart when

> "*investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance*".

This definition builds on previous work by ref. [41], highlighting a broad and comprehensive view of Smart Cities and adopts a holistic and multifaceted[42] view of this urban model.

In particular, this definition presents two main advantages. First, it is inspired by an urban production function approach. With a clear distinction between inputs and outputs, smartness is an intermediate step toward the goal of smart (sustainable) urban growth. Second, the definition decomposes the concept along six dimensions, which can be individually measured and tested, using data from official statistical sources. Therefore, this definition has been among the first ones to be empirically verified[43].

From the previous subsection, it is clear that there are several potential determinants at the urban level explaining the extent of the digital divide. Among these, the Smart City model may also be linked to the digital divide, especially in terms of a framework that can exacerbate digital inequalities, as suggested by some critiques of this concept. Refs. [4,44,45] focus on the factors hampering the potential of Smart City solutions to actually foster quality of life improvements, citing, among other factors, the role of barriers to high-speed connections and IT applications.

Yet, despite vague references to the unequal effects of urban smartness, and the qualitative claims about the spatially heterogeneous impacts that urban smartness may have, to date these two branches remain rather separate. We thus revert to the research question discussed above, viz. "*Is urban smartness associated with a higher digital divide?*".

RESULTS

This section presents our main empirical findings in flour blocks. We first introduce baseline ordinary least squares (OLS) estimates of Eq. (2), explaining the role of urban smartness measured by the indicator aggregating the individual axes of the Smart City definition introduced in Section "Introduction" and described in detail in "Supplementary Materials"—in driving the relevance of the digital divide, our dependent variable, while controlling for other factors (Subsection "Baseline estimates"); next, we run a number of robustness checks meant to deal with potential omitted variable bias (Subsection "Robustness checks"); moreover, we disentangle the role of ownership from that of use of digital technologies (Subsection "Disentangling onership from the use of digital devices"); lastly, we deal with identification of causality by means of three different sets of Instrumental Variables (IV) (Subsection "Instrumental variable estimates").

Baseline estimates

Table 1 shows the results of estimating Eq. (2), Section "Methods", with heteroskedastic-robust standard errors. All over this first table, results are presented as standardized coefficients, i.e. measured in standard deviations; hence, results can be safely interpreted as Standard Deviation unit responses to Standard Deviation large impulses to the right-hand side (RHS) variables. In what follows we will comment in detail on the estimation results related to our main relation of interest, i.e., the one between smartness and the city-level digital divide.

Moving horizontally along the table, Column 1 presents a reduced form model whereby our measure of the digital divide is regressed only against the urban smartness indicator. This first model suggests that a 1 standard deviation increase in urban smartness reduces the digital divide by 1/3 standard deviation. However, because this result may be affected by omitted variable bias, and actually include the role of other factors, the models in Columns (2–6) further include trust, quality of governance, location characteristics, R&D intensity, whether the city plays the role of Country capital, population density, the share of artificial land, and urban GDP.

Throughout these specifications, the parameter estimated for urban smartness remains negatively and significantly associated with the level of the digital divide. In fact, statistical significance never drops below 99 percent. All in all, the specification in Column (6) explains roughly one-quarter of the total linear variance.

Robustness checks

Because the magnitude of the baseline estimates may still be significantly biased due to omitting relevant controls, Table 2 introduces a number of additional regressors that are meant to further isolate our main point estimate. In particular, we also control for:

- Income inequality
- Human capital
- New Member States
- Median age
- Foreign population demographic structure
- 5 G adoption.

The rationale for each control is the following. Income inequalities may be correlated with the digital divide, and this co-existence may jeopardize the correct identification of the association between the digital divide and urban smartness (this hypothesis is empirically verified in Technical Appendix A3). One

Table 1. Baseline estimates.

	(1) Smartness only	(2) Controlling for trust	(3) Controlling for quality of governance	(4) Controlling for location characteristics	(5) Including other controls	(6) Controlling for urban GDP
Urban smartness	−0.296***	−0.173***	−0.174***	−0.248***	−0.245**	−0.258***
	(−3.86)	(−2.93)	(−2.86)	(−2.74)	(−2.50)	(−2.75)
Trust		−0.291***	−0.294***	−0.262***	−0.314***	−0.313***
		(−3.52)	(−3.33)	(−2.69)	(−3.11)	(−3.21)
Regional Quality of Governance			0.006	0.041	0.042	−0.163
			(0.10)	(0.58)	(0.45)	(−1.50)
Dummy, =1 if area is classified as mountainous				0.233***	0.244***	0.208***
				(4.31)	(3.95)	(3.40)
Dummy, =1 if area is located on within-EU borders				−0.013	−0.006	0.001
				(−0.23)	(−0.10)	(0.01)
R&D intensity					0.071	0.031
					(0.88)	(0.40)
Dummy, =1 if city is Country capital					0.023	0.011
					(0.31)	(0.15)
Population density					0.047	0.005
					(0.49)	(0.05)
Share of artificial land					−0.040	−0.092
					(−0.57)	(−1.24)
Log of urban GDP						0.307***
						(2.98)
Observations	252	240	240	184	180	180
Adjusted R^2	0.084	0.145	0.142	0.226	0.225	0.247

Standardized beta coefficients; t statistics in parentheses.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

may also argue that the fractionalization of a city along the racial, age structure, or median age may affect the intensity of the estimated relation. The estimated magnitude of the latter may also be biased due to this being differently structured in Countries with a long history of EU membership and in areas that joined the EU more recently. Lastly, the estimated relation may have recently changed slope due to the emerging diffusion of frontier technologies, such as the 5 G, and this may have caused lagging cities and regions to leapfrog to overcome prior technological holdups.

Columns (1–7) in Table 2 show that none of these checks affects our parameter estimate. The relation between a city's internal digital divide and its level of smartness remains strongly and significantly negative. Standardized beta coefficients oscillate between 0.25 and 0.4, suggesting that a 1 standard deviation impulse to urban smartness corresponds to a 1/3 standard deviation reduction in the digital divide. This evidence seems to disperse the fear that the adoption of digital technologies and a smart planning paradigm is bound to exacerbate digital differences across actors; in fact, our findings go in the exact opposite direction and suggest that cities scoring higher in the smartness axis tend to be characterized by lower levels of the digital divide.

Considering controls, in what follows we provide a general comment on their estimated parameters, highlighting the results of specifications where estimated parameter values are distinguishable from zero.

Focusing on variables related to economic and technical well-being, higher levels of urban GDP are associated with a more pronounced digital divide. The level of R&D sending is instead unrelated to the digital divide.

When considering institutional factors, higher levels of trust are consistently linked to lower levels of the digital divide, while the quality of government at the regional level is negatively and significantly related to the dependent variable in a few specifications.

In terms of geographical variables, mountainous terrain is a factor that significantly affects the level of the urban digital divide, suggesting the existence of physical barriers to the diffusion of digital technologies, while higher shares of artificial land are associated with a lower urban digital divide in some specifications. Population density, in a few specifications, is a mitigating factor in relation to the digital divide, with denser cities characterized by lower levels of it.

Additional factors worth mentioning link the share of the foreign-born population with higher levels of the digital divide and lower levels in the presence of high age fractionalization. Income inequality, the general level of education, being in a New Member State (NMS) and being engaged in a 5G project are not relevant factors that help explain the levels of the digital divide.

Distinguishing ownership from the use of digital devices

Another critique may be directed against the potential risk of mixing ownership from use effects. In fact, owning a digital device does not guarantee its efficient or effective use.

To test this possibility, in Table 3 we compare our baseline estimates (Column 1) with two additional models that maintain the same set of controls, but replace the dependent variable introduced in Section 5 with two where only questions referred to

Table 2. Robustness checks.

	(1) Income inequality	(2) Human capital	(3) New Member States	(4) Median age	(5) Foreign population	(6) Fractionalization of demographic structure	(7) 5G adoption
Urban smartness	−0.395***	−0.412***	−0.240**	−0.381***	−0.201**	−0.271***	−0.265***
	(−3.52)	(−4.65)	(−2.59)	(−3.76)	(−2.22)	(−2.96)	(−2.76)
Trust	−0.532***	−0.154	−0.319***	−0.425***	−0.302***	−0.411***	−0.320***
	(−4.29)	(−1.46)	(−3.29)	(−4.09)	(−3.27)	(−4.22)	(−3.13)
Regional Quality of Governance	0.028	−0.214*	−0.179	−0.119	−0.167	−0.036	−0.153
	(0.23)	(−1.78)	(−1.65)	(−1.10)	(−1.57)	(−0.29)	(−1.40)
Dummy, =1 if area is classified as mountainous	0.207***	0.236***	0.179***	0.181**	0.178***	0.146**	0.200***
	(2.70)	(3.45)	(2.91)	(2.58)	(3.06)	(2.55)	(3.27)
Dummy, =1 if area is located on within-EU borders	0.056	0.046	0.015	0.043	0.005	0.014	0.001
	(0.88)	(0.53)	(0.25)	(0.66)	(0.08)	(0.23)	(0.02)
R&D intensity	−0.052	−0.083	0.035	0.052	0.037	0.134	0.035
	(−0.49)	(−0.92)	(0.45)	(0.55)	(0.48)	(1.64)	(0.44)
Dummy, =1 if city is Country capital	0.201**	0.022	0.052	0.039	−0.099	−0.055	−0.010
	(2.59)	(0.23)	(0.69)	(0.48)	(−1.39)	(−0.73)	(−0.12)
Population density	−0.080	−0.101**	0.002	−0.122**	0.015	−0.010	0.002
	(−0.87)	(−1.98)	(0.02)	(−2.26)	(0.16)	(−0.11)	(0.02)
Share of artificial land	−0.208**	−0.088	−0.108	−0.120	−0.160**	−0.172**	−0.094
	(−2.42)	(−0.88)	(−1.45)	(−1.41)	(−1.98)	(−2.29)	(−1.27)
Log of urban GDP	0.367***	0.344***	0.127	0.383***	0.155	0.262**	0.294***
	(3.04)	(2.74)	(0.75)	(3.56)	(1.45)	(2.52)	(2.87)
Gini Index of income inequality	0.055						
	(0.63)						
% of population with ISCED 5/6 education		0.033					
		(0.40)					
Dummy, =1 if Country is a NMS			−0.221				
			(−1.19)				
Median age of city population				0.115			
				(1.43)			
Percentage of foreign-born citizens					0.282***		
					(3.00)		
Fractionalization index of citizens' age						−0.296***	
						(−3.95)	
Dummy, =1 if city is engaged in 5G pilot projects							0.030
							(0.38)
Observations	90	137	180	127	180	180	179
Adjusted R^2	0.539	0.375	0.249	0.406	0.288	0.302	0.248

Standardized beta coefficients; t statistics in parentheses.
$^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

the ownership of the six technologies mentioned in the Eurobarometer interviews (Column 2) and their regular use (Column 3) were asked. We can thus disentangle the effect of urban smartness on the digital divide that is recalculated for ownership or use alone, respectively.

The relevant (and striking) take-home message of these results is that once we disentangle use from ownership, the negative association between urban smartness and the digital divide remains only when taking ownership into account. In fact, in this case, the estimated parameter is almost twice as large as in the comparable baseline estimates (Column 2 vs. 1). For use, urban smartness is in fact *positively* associated with the digital divide, as suggested in the qualitative literature summarized in Section "Distinguishing ownership from use of digital devices".

Given the statistics about the current extent of the digital divide even in a comparatively developed area such as the EU discussed in the introduction, it seems fair to argue that the Smart City paradigm is slowly penetrating the everyday life of actors, facilitating on the one hand the progressive diffusion of ICTs, but failing so far on the other hand to diffusing the positive effects to all actors. In other words, we may be facing a medium-run transition towards the increasing *diffusion* and *use intensity* of ICTs, but the latter may be lagging. It would be therefore relevant to follow up on this study in a few years to collect further cross-sections of data allowing us to compare these findings with more recent evidence.

Lastly, it is worth stressing that when averaging out the ownership and use effect (Column 1), the final impact of urban smartness on the

Table 3. Disentangling ownership from use effects.

	(1) Baseline estimates	(2) Ownership estimates	(3) Use estimates
Urban smartness	−0.258***	−0.338***	0.147*
	(−2.75)	(−3.57)	(1.74)
Trust	−0.313***	−0.367***	0.053
	(−3.21)	(−3.93)	(0.64)
Regional Quality of Governance	−0.163	−0.107	−0.216*
	(−1.50)	(−1.02)	(−1.84)
Dummy, =1 if area is classified as mountainous	0.208***	0.188***	0.127*
	(3.40)	(3.01)	(1.72)
Dummy, =1 if area is located on within-EU borders	0.001	−0.006	0.018
	(0.01)	(−0.09)	(0.42)
R&D intensity	0.031	0.089	−0.154**
	(0.40)	(1.14)	(−2.39)
Dummy, =1 if city is Country capital	0.011	−0.069	0.234**
	(0.15)	(−1.12)	(2.29)
Population density	0.005	−0.009	0.039
	(0.05)	(−0.10)	(0.67)
Share of artificial land	−0.092	−0.097	−0.015
	(−1.24)	(−1.35)	(−0.15)
Log of urban GDP	0.307***	0.338***	0.012
	(2.98)	(3.32)	(0.11)
Constant term	0.060	0.029	.091**
	(0.06)	(0.099)	(0.038)
Observations	180	181	180
Adjusted R^2	0.247	0.315	0.091

t statistics in parentheses.
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

urban digital divide does remain significantly negative, and this result will be taken into account for our final empirical test, dealing with the potential endogeneity bias in our estimates.

Instrumental variables estimates

This last empirical subsection presents results dealing with the identification of causality in the estimated relations. In fact, endogeneity may influence (by biasing and making it inconsistent) the urban smartness-digital divide relation. This may happen because urban smartness is actually explained by a second linear equation including unobservables that are correlated with variables appearing in Eq. (2). This makes the smartness treatment correlated to the error term in the main specification[46].

To deal with this potential issue, we need an instrument allowing to isolate variation in urban smartness but not being correlated with the error term in Eq. (2) (where the variance left unexplained by our estimates lies). We propose to resort to the following three candidates:

- Bike-sharing intensity;
- breadth and depth of digital broadband networks;
- time-lagged specialization in business services and public administration.

The rationale of the three instruments is as follows. Bike sharing is a relatively recent phenomenon offering affordable and environmentally-friendly means of transportation to a wide urban audience. It has thus been often linked to the Smart City paradigm[47,48]. At the same time, it seems hard to think of any link between the endowment of cities with bike-sharing systems and urban areas' digital divide.

The second set of instruments relates to long-time lags of broadband infrastructure. This has been used for the first time as an instrument in ref. [8], to which the interested reader is referred for further technical details. The idea is that spatial variation in early broadband infrastructure would be linked to urban smartness, while not causing higher levels of *within-city* digital divide.

The third and last set of instruments relates to long-time lags of employment specialization in industries linked to the emergence of the Smart City paradigm. We focus in particular on the average share of employment in two tertiary activities (public administration and financial and business services) over the period 1989–2012. These two sectors are arguably providing the highest demand, and support, for smart urban technologies; at the same time, it is hard to think of any direct link between these two industries and the subsequent degree of within-city digital divide.

The results of these three additional regressions are shown in Table 4.

In terms of instruments, Table 4, Column (1) uses the intensity of bike sharing alone; Column (2) the intensity of bike sharing and the breadth and depth of digital broadband networks; and Column (3) the average 1989–2012 specialization in business services and public administration.

Across all models, the relation between urban smartness and the within-city digital divide remains significant at least at the 10 percent level (Column 3), or 5 percent (Columns 1 and 2). As often happens with IVs, the estimated parameter also becomes larger in magnitude.

From a statistical point of view, all three specifications pass the usual tests, as summarized in Table 5:

Because Models (2) and (3) make use of multiple instruments, in this case, we also performed the IV test of redundancy. In this case, the redundancy tests consider the redundancy of the instruments beyond bike sharing intensity. In Column (2) the redundancy test does not reject (although slightly so: the LM test's value is 4.414, p value 0.11) the null of redundancy, while in Column 3 we obtain a strong rejection (LM = 11.465***, p value <0.01).

Moreover, because the Stock-Yogo critical values are only valid under the traditional assumption of spherical errors[49], we also calculated the robust test for weak instruments. Results for the three models in Table 4 are presented in Table 6.

In light of both these sources of evidence, model 3 in Table 4, which also shows no evidence of weak instrumentation, is our preferred specification. Based on this specification, we present some back-of-the-envelope calculations important to interpret our findings. Figure 1 plots the marginal effects of urban smartness on the intensity of the within-city digital divide.

The X-Axis reports urban smartness in quintiles, while the Y-Axis shows the predicted value of the digital divide for the same quintiles. In interpreting our preferred specification, it is important to highlight that the level of urban smartness is characterized by a few outliers, which, to the very right-hand side tail of the smartness distribution, include London. As a consequence, the right tail may be characterized by substantial variance that would make it difficult to interpret the estimated relation in a purely linear fashion. In fact, the rather broad confidence interval around the fifth quintile of the distribution of Fig. 1 does suggest that for a very high level of urban smartness, the negative association with the urban digital divide may be no longer significant. Instead, confidence bands remain very narrow up until the fourth percentile of the distribution.

Table 4. IV estimates of the general model.

	(1)	(2)	(3)
Urban smartness	−0.658*	−0.610*	−0.359+
	(−2.23)	(−2.43)	(−1.72)
Trust	−0.411**	−0.414***	−0.389***
	(−3.26)	(−3.40)	(−4.01)
Regional Quality of Governance	−0.088	−0.099	−0.072
	(−0.72)	(−0.89)	(−0.54)
Dummy, =1 if area is classified as mountainous	0.109	0.119	0.122
	(0.97)	(1.10)	(1.34)
Dummy, =1 if city is located on within-EU borders	0.136+	0.127+	0.059
	(1.88)	(1.91)	(0.88)
R&D intensity	−0.117	−0.118	0.054
	(−0.85)	(−0.89)	(0.50)
Dummy, =1 if city is Country capital	0.167+	0.164+	−0.041
	(1.82)	(1.79)	(−0.38)
Population density	−0.090	−0.090	−0.140*
	(−1.41)	(−1.45)	(−2.48)
Share of artificial land	−0.287**	−0.284**	−0.142
	(−3.17)	(−3.09)	(−1.34)
Log of urban GDP	0.367*	0.343*	0.255+
	(2.25)	(2.27)	(1.69)
Median age of city population	−0.037	−0.035	0.111
	(−0.46)	(−0.45)	(1.34)
Percentage of foreign-born citizens	0.310*	0.323*	0.184
	(2.32)	(2.50)	(1.20)
Fractionalization index of citizens' age	0.102	0.103	−0.199
	(0.92)	(0.94)	(−1.56)
Instruments used	Intensity of bike sharing	Intensity of bike sharing; breadth and depth of digital broadband networks	Average 1989–2012 specialization in business services and public administration
Observations	68	68	94
Adjusted R^2	0.578	0.595	0.440

t statistics in parentheses.
$+p < 0.1$, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Table 5. Standard IV test for models in Table 4.

Model	Underidentification test (Kleibergen-Paap rk LM statistic)	Weak identification test (Cragg-Donald Wald F statistic)	Hansen J over-identification test
1	7.22***	8.660*	n.a.
2	10.06**	3.950*	0.088
3	13.142***	8.925*	1.686

Table 6. Weak IV tests for the models in Table 4.

Model in Table 4	Effective F statistic	2SLS Critical Values ($\tau = 10\%$)
1	6.876	23.109
2	3.858	11.638
3	8.618	6.866

DISCUSSION

This paper has for the first time linked two previously rather disconnected branches of the urban economics literature, one dealing with the relevance of the digital divide, the other calling for the adoption of the Smart City paradigm as a means to efficiently manage cities. We did so with an eye to the lack of empirical evidence about the alleged negative role played by the Smart City approach in actually causing increases in the digital divide, thus further worsening yet another dimension of intra-urban inequalities.

Our empirical work, based on a number of robustness checks, and the adoption of econometric techniques dealing with identification, actually suggests that Smart Cities also tend to be less affected by the urban digital divide. While the evidence on this result appears rather robust, two caveats appear particularly relevant:

1. The negative impact of smartness on the digital divide seems to be driven mostly by an ownership, rather than a use, effect. This point will have to be cross-checked in the near future, to verify whether the further diffusion of ICTs will also prompt an increased awareness of their efficient use;
2. Digging into the distribution of urban smartness, our results suggest that the negative association between urban smartness and the digital divide is at work only until the

medium-upper levels of the former. For very high levels of urban smartness, no statistically significant association (in either direction) is detected.

These findings also suggest particularly relevant policy implications. The Smart City paradigm has now been around for more than a decade and the time is now ripe to start drawing evidence-based conclusions on its effectiveness. After the first wave of empirical studies dealing with its actual impact [50], our own work has now shed more light on its distributional effects.

Against prior fears about the negative effect that a wise adoption of Smart technologies would have on the weakest segment of the urban population (mostly not followed by empirical verification), evidence is now mounting on the fact that, if coupled with widespread and pervasive investment in human and social capital, supporting their skilled adoption and use, ICTs are actually an excellent instrument for democratic and effective planning of future cities.

Practical examples of implementing Smart Cities with the goal of reducing intergenerational, territorial, and gender divides typically hinge on the capacity to involve broad segments of the population. For instance, Santiago (Chile) participated in the 2022 Smart City Expo World Congress, where its metro area's governor stated that *"we have an open government approach, and when we do our town hall meetings, we show the outcomes of the meetings and then the co-designing of social programs. Instead of having highly qualified technicians, we include people to be active actors of the design of these policies"*[51]. The relevance of usage (and capability) disparities even in places with decent connectivity is in fact deemed so relevant that guidelines by the UN-Habitat program are available to public authorities, Non-Governmental Organizations, and communities to address this aspect[52].

These concluding remarks provide food for thought on the (non-negligible number of cases of) top-down Smart Cities planned all over the world. Cities created from the top down face a substantial risk of not reaping the benefits from investment in ICTs (at best), or, even worse, may be associated with substantial chances to create dystopic futures where few gain from their hyper-connected urban locations, while most other urban dwellers remain disconnected from such benefits.

METHODS

Econometric approach

In order to explore our research question, we adopt a two-stage procedure. In the first stage, we compute a measure of the digital divide at the urban level (*within-city digital divide*) with individual (micro) data, while in the second we aggregate this information at the urban level and explore its determinants, with a specific focus on the role of smartness.

In the first stage, the intensity of the digital divide is calculated as the within-city standard deviation (as a standardized measure of within-unit variation) in the distribution of individual responses to the latest territorialized version of the European Values Study (data set collected in 2017). Following the approach used in ref. [53] for assessing and measuring agglomeration advantages, and in ref. [54], to assess urban risk attitude, individual responses are predicted after regressing ICT ownership and usage against relevant individual traits. These are suggested by the analysis of previous literature on the determinants of the digital divide presented in Section "Results", including education, gender, income, age, student/employed/retired status, and Country fixed effects (Eq. 1):

$$\text{prob}(\text{digital owenrship} - \text{usage}_i) = \alpha + \beta_1 * \text{education}_i + \beta_2 * \text{gender}_i + \beta_3 * \text{age}_i + \beta_4 * \text{working\_status}_i + \beta_5 * \sum_{c=1}^{n} \text{Country}_{i,n} \tag{1}$$

For each of the 22,628 individuals for which all observations about the above-mentioned variables are available, we calculate the predicted linear probability of actually owning or using one of the digital technologies discussed in Section 4 (Technical Appendix A.2 provides further details on the questions included in the analyses, as well as on the results of first stage regressions). Responses are interpreted as probabilities due to their dichotomous nature.

In the second stage we aggregate these predicted linear probabilities by calculating their standard deviations at the urban level, our measure of the digital divide (capturing both digital technologies ownership and use), and examine the link between urban smartness and the digital divide, along with a set of aggregate determinants suggested in the previous Sections, by empirically testing the following specification (Eq. 2):

$$\text{Digital divide} = f(\text{GDP; R\&D; institutions; social capital; geographical factors; population density; urban smartness}) \tag{2}$$

On the left-hand side, the variable capturing the intensity of the digital divide is obtained as the standard deviation of predicted values obtained from Eq. (1) at an individual level for all cities in the data set (Eq. 3):

$$\text{digital divide}_c = \text{SD}_c\left(\widehat{\text{digital}_i}\right) = \sqrt{\frac{\sum_{i=1}^{n}\left[\widehat{\text{digital}_i} - \overline{\text{digital}}\right]^2}{(n-1)}} \tag{3}$$

where $i = 1,\ldots, n$ refers to the number of individuals in each city c, and notations with a hat on top refer to values predicted in the instrumental regression in Eq. (1).

As for factors explaining the intensity of the digital divide, all city-specific factors included on the Right-Hand Side of Eq. (2) are potentially expected to be good predictors of the propensity of a city to adopt and use digital technologies, and suffer more or less severely from internal digital divide, we are particularly interested in the statistical link between the intensity of the digital divide and urban smartness. In other words, our empirical work seeks to identify the role of urban smartness in potentially exacerbating, or minimizing, issues of within-cities digital divide.

Data

A database covering 181 European cities has been specifically assembled from different sources (see Table 7). Data for the independent variables is lagged with respect to the dependent variable in order to capture the long-term nature of the relations at play and to reduce the problem of endogeneity.

Data from Eurobarometer 88.4, used to estimate the digital divide, cover both availability and the ownership of the following IC technologies as well as the frequency of their use (See Technical Appendix A.2 for details on the Eurobarometer questions used to measure individual indicators).

- Desktop computers
- Laptop computers
- Tablets
- Smartphones
- Home internet connection
- Standard mobile phone

The idea to include multiple technologies in our empirical estimates is based on the fact that, in contrast with the early

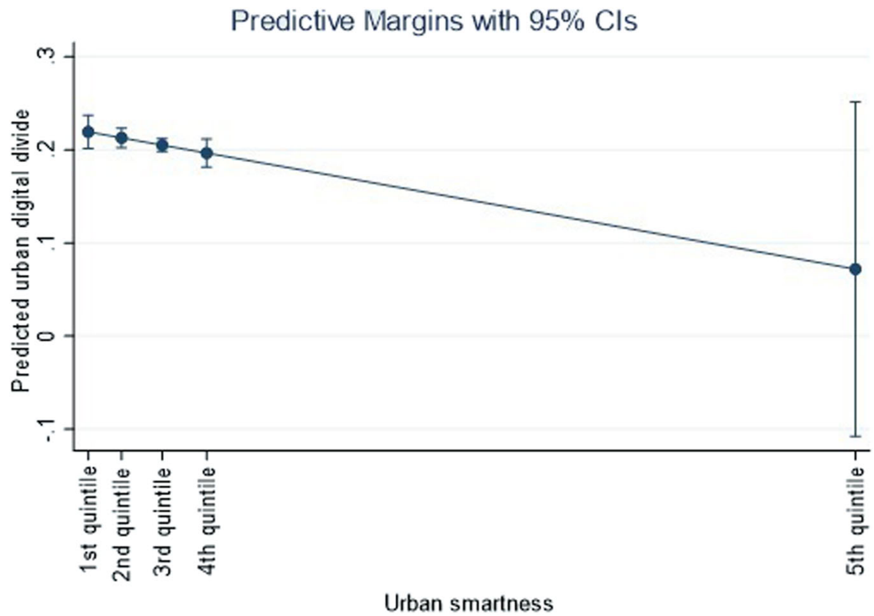

Fig. 1 Marginal effects of urban smartness on the urban digital divide. Source: Authors' elaboration. Note: Predictive margins are represented with 95 percent confidence intervals, and indicated with a blue vertical line.

Table 7. Data set for the empirical analyses.

Indicator	Source of raw data	Period measured	Formula/Methodology
Digital divide	Eurobarometer 88.4	2017	Standard deviation of the predicted values obtained from regressing ICT ownership and usage against relevant individual traits
Urban smartness	European Value Study/ EUROSTAT	2008–2012	Indicator obtained as an unweighted average of six Principal Component Analyses covering the six axes of the Caragliu et al. (2011) definition (Human capital; Social capital; Transport infrastructure; ICT infrastructure; Natural resources; E-government). Original indicator was first presented in Caragliu and Del Bo (2015); see Table A.1 in Technical Appendix A1 for more details
Real GDP	EUROSTAT	Average 1995–2010	GDP in constant market prices (base year = 2010)
R&D	EUROSTAT	Average 2008–2012	Gross expenditure in R&D over GDP
R&D intensity	EUROSTAT	2010	Percentage of regional GDP invested in R&D
Fractionalization index of citizens' age	Eurobarometer 88.4	2017	Defining as s the share of interviewees in the Eurobarometer sample aged x, the index is equal to 1- HHI_x, where $\mathrm{HHI}_x = \sum_{x=15}^{99} s_x^2$
Median age of city population	Eurobarometer 88.4	2017	Median of the interviewees' sample
% of population with ISCED 5/6 education	EUROSTAT	Average 1995–2010	-
Gini Index of income inequality	EVS; Introduced in Caragliu and Del Bo (2022)	2017	Defining y as income, x as equalized income, (With x defined as the ratio between y and a function of personal traits.) $F(X)$ the distribution of income, and $\mu(F)$ the mean of this distribution, the Gini index can be expressed as the Gini index of income inequality is calculated as $I_{\mathrm{Gini}} = \frac{1}{2\mu(F)} \iint \lvert x - x' \rvert dF(x) dF(x')$,
Trust	European Value Study	2009–2010	% of respondents "Most people can be trusted" to the question "Generally speaking, would you say that most people can be trusted or that you can't be too careful in dealing with people?"
Quality of government	Charron et al. (2014)	2010	Principal component analysis
Share of artificial land	EUROSTAT/LUCAS (*Land Use and Cover Area frame Survey.*)	2009	-
Dummy variables	EUROSTAT/Authors' elaboration	2010	Dummy =1 for • Mountainous NUTS3 regions • Regions located on within-EU borders • Country capital cities • Regions located in CEECs • Cities engaged in 5G pilot projects
Population density	EUROSTAT	Average 1995–2010	Urban area population/ Area in sq. kms.

period of diffusion of ICTs, now people often have access to several devices, and each can contribute individually, or jointly with others, to let people reap the benefits of the digital society.

DATA AVAILABILITY

Micro data used to calculate the city-specific intensity of the digital divide are obtained on the basis of Eurobarometer 88.4 survey data, available at https://search.gesis.org/research_data/ZA6939.

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AUTHOR CONTRIBUTIONS

Both authors designed the study, interpreted the results, collected the data, performed the analyses, and revised and edited the manuscript. A.C. is more specifically responsible for Sections 3.1 and 3.4; C.F.D.B. for Sections 3.2 and 3.3. Both authors approved the final version of the article.

COMPETING INTERESTS

The authors declare no competing interests.

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