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Urban density and Covid-19: towards an adaptive approach

SPECIAL COLLECTION: URBAN DENSIFICATION

SYNTHESIS

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ABSTRACT

A literature review and analysis is presented on the influence that urban density has on the diffusion of Covid-19. Six main categories of factors are identified: urban settlement, socioeconomic factors, urban services, urban environment, policies and time. At this stage there is no scientific consensus about the effect of density. Urban connectivity appears to play a bigger role in the diffusion of the pandemic. Important gaps are identified in the literature on the compared governance of risk and the density at the building level. More research should be directed to the evaluation of adaptation measures adopted by cities, communities and individuals. The relation between urban density and health issues should be framed in a vulnerability perspective, considering the interplay between exposure, sensitivity and the adaptive capacity of cities.

POLICY RELEVANCE

Given the lack of consensus between scientific studies, it is too early to reverse the existing policies and recommendations that promote dense and compact development. Instead, more attention should be paid to the types/conditions of density and the equitable access to urban services and green infrastructures in order to minimise risks and lower the burden of social-distancing measures in dense environments. Resilience policies should focus on addressing deficiencies in the existing urban environment that are at the core of the epidemic outbreak. These policies should be based on a close collaboration with local communities and intermediate actors (*e.g.* planners, architects, health officials, *etc.*) to address social, economic and technological inequalities.

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1. INTRODUCTION

First identified in December 2019, Covid-19 rapidly propagated across countries and cities of the world, causing more than 49.7 million confirmed cases and 1.2 million deaths globally (as of November 2020, and still rising) since the start of the pandemic (WHO 2020). Besides disruptions in supply chains and international travel restrictions, the pandemic affected a large share of the world population in its everyday life. Non-pharmaceutical interventions (NPI) were at the core of national strategies to contain the spread of the epidemic as time was required to develop an effective vaccine(s). These NPIs were typically based on a combination of measures, including face covering, social distancing, handwashing, sanitising and improved indoor ventilation, with restrictions on domestic and international travel (Wells *et al.* 2020). Stay-at-home policies had to be adopted at the city or national scale in many countries. These stringent measures were typically followed by isolation for those who had been tested positive, and quarantining for at-risk individuals.

All these NPIs had important consequences for the built environment. Many community facilities and shops were closed. Public transport was largely disrupted for weeks or months. A majority of traditional workplaces were suddenly deserted, and teleworking was implemented, mainly from home. The uneven development of the virus in different places rapidly raised questions about the characteristics of the built environment that may contribute to its diffusion. As spectacular spikes of Covid-19 cases initially developed in large agglomerations such as New York, London or Milan, urban density was quickly suggested as a possible factor that may help the spread of the virus within cities:

> The very same clustering of people that makes our cities more innovative and productive also makes them, and us, vulnerable to infectious disease.
>
> (Florida 2020: n.p.)

The discursive link made between globalisation, densification and the diffusion of the virus rapidly nurtured an anti-urban sentiment, which would soon be directed against specific groups and inhabitants of bigger cities, especially through social media (Boterman 2020).

Intuitively, density is associated with closer contacts between individuals, and:

> most epidemic diseases depend on the clustering of human hosts into densities that are able to sustain an infection chain through contact diffusion.
>
> (Ali & Keil 2007: 1-208)

A higher urban density can be related to a higher chance of contact, exposure and interactions between people, and can thereby, indirectly, cause an increase in Covid-19 cases (Jamshidi *et al.* 2020). As Covid-19 is known to circulate through airborne particles and contact with contaminated surfaces, it is quite logical to consider that denser environments, and especially complex multi-storey buildings, may be associated with more frequent contacts with the virus (Acuto 2020). History also teaches us that the urban environment is prone to the spread of contagion and epidemic outbreaks (Boterman 2020; Ali & Keil 2007; Connolly *et al.* 2021; Reyes *et al.* 2013; Bhadra *et al.* 2020). However, the relation between health and the urban environment should be addressed in a vulnerability perspective, considering the adaptive capacity of cities. Several urban innovations can indeed be traced back to the fight against infectious disease. The first sewage system was developed in ancient Rome as a reaction against diseases such as dysentery and typhoid. The widening of streets and spectacular extension of the sewers in Baron Haussmann's Paris was partly directed to fighting cholera. And the access to sun and daylighting was presented by the modern movement as a cure against tuberculosis (Pinheiro & Luís 2020).

Globalisation increased the exposure of larger cities, especially those most connected to the flows of capital, goods and people (Ali & Keil 2007). How should our contemporary cities adapt to the new Covid-19 pandemic and, more generally, to epidemic outbreaks? Several planning policies are presently promoted in-fill development and densification in order to reduce land consumption, greenhouse gas (GHG) emissions and an efficient public transport network. Should this approach be revised or abandoned at the light of the recent pandemic? Before answering these questions, it is essential to identify the factors governing the diffusion of Covid-19 in the urban environment. This paper will review the literature published in this domain, focusing on the observed relation between urban density and Covid-19.

As will be explained below, there appears to be no consensus at this stage about the effect of density on the diffusion of Covid-19. In order to address the divergence between recent studies, consideration is given to both statistical models and the variables selected in the literature. This will help to identify possible research avenues in the domain of resilience to epidemic outbreaks.

Given the lack of consensus between scientific studies and clear evidence, it is too early to backtrack from previous policies related to the promotion of dense and compact development. More importantly, resilience policies should focus on addressing deficiencies in the existing urban environment that are at the core of the present epidemic outbreak and will remain for the months, if not the years, to come. The debate on the impact of density on Covid-19 should therefore be directed to devising adaptation strategies, tailored to each urban environment, considering the exposure and sensitivity to risks of the urban environment.

The paper is structured as follows. The next section briefly outlines the approach and method. The effects and factors that have been considered in the scientific literature as related to the impact of urban density on Covid-19 up to the present are then identified. These are followed by an explanation about why there are divergences between studies at this stage, and possible avenues for further research are then formulated.

2. APPROACH AND METHOD

The objective of this paper is to highlight the convergences and divergences between studies about the relation between Covid-19 and the built environment, considering both their conclusions and their methodology. A study published in August 2020 estimated that some 23,634 scientific papers have been issued between 1 January and 30 June 2020 on Covid-19 (Teixeira da Silva *et al.* 2021). This plethora obviously did not stop in early July. A keyword search for Covid-19 on ScienceDirect (11 November 2020) returned some 30,000 results. According to Brainard (2020: 1), 'scientists are drowning in Covid-19 papers'. The focus of the present paper is on a limited set of authoritative papers published since the crisis, and only those in scientific journals. The identification of relevant papers was based on a combination of queries on ScienceDirect with traditional cross-bibliographic analysis. The queries were based on the following search terms: 'urban density', 'COVID', 'ecological study' and 'statistical analysis'.

Before the outbreak of Covid-19, much of the debate about the health impact of urbanisation concentrated on chronic diseases, *e.g.* obesity, diabetes and heart disease (Connolly *et al.* 2021). The surge of such diseases has been associated with several factors, amongst which are sedentarism, car dependency, monofunctionality and low-density urban environments (Owen *et al.* 2004; Giles-Corti *et al.* 2016; Sugiyama *et al.* 2020). This was especially the case in the literature on walkability, although the relation between walkability and health is not trivial as walkability is often related to urban deprivation (Su *et al.* 2017). These studies were not considered in the present review which deliberately focused on Covid-19 and its observed relation with urban density.

Table 1 identifies the selected papers and summarises their key conclusions about the observed effects of urban density on the number of reported cases and deaths due to Covid-19. It highlights the divergence between studies in this field. Many authors do not observe the significant effects of urban density on Covid-19. Those authors who measure a significant effect may observe a positive or a negative influence of increased urban density on Covid-19 according to the dependent variable adopted (number of cases versus number of deaths). As the statistical models used by different studies vary, different methods are used to measure the significance of the results. Information provided in ***Table 1*** is based on the original authors' own conclusions in most cases. Most studies used $p < 0.05$ as a minimum threshold for significance.

Table 1 further highlights that the scale of analysis largely varies between studies, from the agglomeration level to the province or cross-national evaluations. Some studies are focused on cities, while others would consider entire politico-administrative units, such as Italian regions, aggregating urban and rural areas.

REFERENCE	EFFECT OF URBAN DENSITY ON THE NUMBER OF REPORTED CASES	EFFECT OF URBAN DENSITY ON THE NUMBER OF DEATHS DUE TO COVID	DEFINITION OF DENSITY	UNIT OF ANALYSIS
Angel *et al.* (2020)	+	n.s.	Share of the population living at high density (> 10,000 persons per square mile)	US Metropolitan Statistical Areas
Boterman (2020)	n.s.	n.s.	Share of the population living in high densities (> 1500 people/km^2)	Dutch municipalities
Carteni *et al.* (2020)	+	Not considered	Number of inhabitants/km^2 in the capital of the region	Italian regions (20)
Fang & Whaba (2020)	–	Not considered	Number of inhabitants/km^2	284 Chinese cities (not considering cities from Wuhan)
Hamidi *et al.* (2020)	n.s.	–	(Number of inhabitants + number of jobs) per square mile	913 counties of US metropolitan areas
Lin *et al.* (2020)	+	Not considered	Number of inhabitants/km^2	16 provinces and four municipalities of China
Qiu *et al.* (2020)	–	Not considered	Number of inhabitants/km^2	288 Chinese cities, excluding cities in Hubei province
Sigler *et al.* (2020)	+	Not considered	Number of inhabitants/km^2	84 countries
	–		Maximum urban density	
Sirkeci & Yücesahin (2020)	n.s.	Not considered	Number of inhabitants/km^2	110 countries
Feng *et al.* (2020)	+	Not considered	Total persons per pixel (500 × 500 m) (*www.worldpop.org*)	Urban cells in China (resolution of 500 m × 500 m)
Jamshidi *et al.* (2020)	+	Not considered	Urban population/urban area (km^2)	All (3006) US counties
Amdaoud *et al.* (2020)	Not considered	n.s.	Number of inhabitants/km^2	377 European regions in 28 countries
Zhang & Schwartz (2020)	+	+	Number of inhabitants/km^2	1624 US counties with 16 or more cases
Whittle & Diaz-Artiles (2020)	+	Not considered	Number of inhabitants/km^2	New York City zip codes with detected cases
Rodriguez-Villamizar *et al.* (2020)	Not considered	n.s.	Number of inhabitants/km^2	772 Columbian municipalities

Table 1: Observed effects of urban density on Covid-19.

Note: ± = Positive/negative and significant correlation between urban density and number of Covid-19 cases/deaths; n.s. = non-significant correlation.

Table 1 highlights that there are major differences amongst studies about the observed effects of density on the number of cases and the number of deaths related to Covid-19. An increase of Covid-19's effects with urban density can be related to the proximity between people and increased probability of interpersonal contacts (Jamshidi *et al.* 2020; Whittle & Diaz-Artiles 2020). Dense urban environments appear as offering more opportunities for the virus (Sigler *et al.* 2020).

CATEGORIES	FACTORS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Urban settlement	Urban density	×		×	×	×	×	×	×	×	×	×	×	×	×	×
	Internal connectivity (size of the population, share of the urban population, *etc.*)	×	×	×	×	×			×			×				×
	External connectivity (travel time from the identified clusters, *etc.*)				×	×	×		×	×	×					
Socioeconomic	Age, life expectancy	×		×		×			×	×			×	×	×	×
	Size of households		×						×							
	Economic income, % of college-educated, human development index, gross domestic product (GDP) per capita, share of the uninsured population, Gini index of disparity		×	×		×		×	×	×			×	×	×	×
	Ethnicity, immigration		×			×								×	×	
	Cultural factors (attendance at church)			×												
	Health factors (pre-existing conditions, % of smokers)			×		×							×			×
Urban services	Hospitals (intensive care unit (ICU) bed rate, primary care physician rate, number of doctors)					×		×					×		×	×
Urban environment	Air pollution				×	×										
	Climate factors (air temperature, relative humidity)				×		×	×				×				
Policies	Governance (index of good governance)												×			
	Number of tests (per inhabitant or per day)		×		×	×								×		
	Stay at home, closed management policies, mask wearing					×		×				×				
Time dimension	Time since the outbreak at the city level	×				×	×		×		×	×	×			×

Table 2: Factors considered in the studies.

Sources: 1 = Angel *et al.* (2020); 2 = Borjas (2020); 3 = Boterman (2020); 4 = Carteni *et al.* (2020); 5 = Hamidi *et al.* (2020); 6 = Lin *et al.* (2020); 7 = Qiu *et al.* (2020); 8 = Sigler *et al.* (2020); 9 = Sirkeci & Yücesahin (2020); 10 = Feng *et al.* (2020); 11 = Jamshidi *et al.* (2020); 12 = Amdaoud *et al.* (2020); 13 = Zhang & Schwartz (2020); 14 = Whittle & Diaz-Artiles (2020); and 15 = Rodriguez-Villamizar *et al.* (2020).

A decrease in Covid-19's effects is explained by an improved healthcare structure in dense urban environments and a better compliance with stay-at-home and social-distancing policies in dense cities (Hamidi *et al.* 2020). Some differences may also be related to the increased awareness of the urban public or variations in testing and reporting mechanisms when compared with more scattered built environments.

3. URBAN FACTORS AT PLAY IN THE PANDEMIC: A SYSTEMIC ISSUE

The multifactorial nature of the diffusion of Covid-19 and its outcomes in terms of deaths is acknowledged by most authors considered in this review. All the analysed studies hence tend to combine different factors, apart from urban density, so as to explain the respective role of these factors in the pandemic. Studies consulted for the preparation of this article mainly relied on so-called aggregated models, *i.e.* models that compare the performance of groups or areas between them. The development of disaggregated models, at the household or individual levels, would require more time for the acquisition of data and calibration/validation exercises. Generally, the range of effects and factors considered by statistical models are heavily dependent on the availability of the data, which largely vary across countries.

Six main categories of factors are usually identified in the literature (***Table 2***). A first type of factor is related to the settlement pattern. This category obviously addresses urban density, but also internal and external connectivity. Urban density is usually measured through the number of inhabitants/km^2. None of the studies consulted in this review included indicators of morphological density, as, for instance, the ground space index (GSI) or floor space index (FSI) (Berghauser Pont & Haupt 2010). Internal connectivity typically refers to the number of trips/connections within an urban area, while external connectivity refers to the number of connections between different urban areas or cities.

Internal connectivity can be approached by the number of inhabitants in the metropolitan area (Hamidi *et al.* 2020; Stier *et al.* 2020), the number of jobs accessible within a given time from one place (Hamidi *et al.* 2020) or the number of trips in a given reference period (Cartenì *et al.* 2020). More sophisticated measures imply the use of the Google mobility report available at the national level (Bryant & Elofsson 2020). Internal connectivity is typically related to mobility between urban, peri-urban and rural areas, which may fuel the diffusion of the disease due to increased contacts with pathogens and the intrinsic heterogeneity between urban dwellers, a kind of 'forced solidarity' (Connolly *et al.* 2021) that may be especially acute in some cities (Florida 2020). Ideally internal connectivity should be measured dynamically so as to cope for the observed adaptation of inhabitants, whether spontaneously or due to travel restrictions.

External connectivity can be measured in absolute terms, *e.g.* through the annual passenger enplaning movements per 10,000 population (Hamidi *et al.* 2020), or in reference to some initial clusters of the first epidemic outbreak, *i.e.* Wuhan in China or Codogno near Milan, Italy (Cartenì *et al.* 2020). Modelling external connectivity requires data about flows between cities that may inform a topological or network approach of diffusion (Ali & Keil 2007). It may be related to the large flows of visitors in superdense cities such as New York or London, or the movement of people and goods associated with industrial centres such as Wuhan, Detroit (US) or northern Italy (Florida 2020).

A second type of factor is related to the socioeconomic characteristics of a place. The elements usually considered are the mean age of the population or their life expectancy, as the severity of Covid-19 is highly related to age (Hamidi *et al.* 2020). Personal economic circumstances influence the number of confirmed cases and deaths (McPhearson *et al.* 2020), especially since income is associated with different levels of opportunities with regard to teleworking as well as access to healthcare (Florida 2020). This category of factors can also include the composition of households given that part of the transmission can occur between members of a family. Some studies considered race, immigration and ethnicity (Hamidi *et al.* 2020). Inhabitants living in immigrant neighbourhoods were less likely to be tested (Borjas 2020). Boterman (2020) considers cultural factors such as attendance at church as well as pre-existing public health conditions (overweight, hypertension, cardiovascular illness). Gender has not often been studied as a potential factor even though it is usually considered in most epidemiological studies (Whittle & Diaz-Artiles 2020).

The third category of factor is related to the type of urban services present in the area. The presence of health centres and hospitals may contribute to alleviate the impact of the pandemic (Neiderud 2015), especially in terms of severity and number of deaths (Hamidi *et al.* 2020). Some research addressed the presence and intensity of airport hubs, which overlaps with external connectivity (Hamidi *et al.* 2020). Quite interestingly, none of the studies reviewed so far included variables related to the availability of potable water. It may be an issue of importance through the impact on hand-washing practices and the concentration of inhabitants in 'infrastructure deserts' where water is not available at home (Gupte & Mitlin 2020; Connolly *et al.* 2021). This may be related to the fact that none of the statistical studies reviewed for this paper was developed in a Global South context, most certainly due to a lack of data, while water poverty and its impact on health is arguably more consequential in these countries.

The fourth category of factors considered in the literature concerns the quality of the urban environment, and more specifically air pollution that has soon be recognised as a potential vector of diffusion of Covid-19 (Pluchino *et al.* 2020). Several contaminants have been considered at this regard, the most important one being the concentration of particulate matter (PM) pollutant (Cartenì *et al.* 2020; Rodriguez-Villamizar *et al.* 2020). Climate factors, as, for instance, air temperature and relative humidity, are also considered in some studies, which observe that the warmer areas of the country are usually related to a lower virus contagion (Cartenì *et al.* 2020; Lin *et al.* 2020).

The fifth category of factors considered in the literature concerns the range of NPI policies adopted by local or national authorities. Social distancing measures, face-covering and hand-sanitising may have an impact on the diffusion of the disease, considering urban areas with a same density. The same is true for travel restrictions, stay-at-home measures and obligations to quarantine. Hamidi *et al.* (2020) control for the level of adherence to social distancing though a variable related to the share of the population staying at home. The number of cases is also influenced by the type of test-and-tracing policies and practices set in place (Boterman 2020; Cartenì *et al.* 2020; Hamidi *et al.* 2020). This last variable may present important interactions with urban density as large-scale testing was more rapidly implemented in large metropolitan areas, still with important disparities between neighbourhoods (Borjas 2020). Ferrari *et al.* (2020) compared the combined impact of urban density and adoption of a contact-tracing app in Italian cities. They highlight that the effects of urban density would easily be compensated for by the increased use of a contact-tracing app by the population. Amdaoud *et al.* (2020) introduced an indicator of good governance so as to measure the incidence of open-government principles and transparency on the adoption of NPI policies by the general public.

Finally, time is the sixth category of factors influencing the diffusion of Covid-19, given the self-reinforcing nature of any epidemic outbreak and the adaptation mechanisms progressively implemented at the local level (Angel *et al.* 2020). Defining the start date and reference periods for the analysis may change the results as the epidemic outbreak typically moved along the different tiers of the urban hierarchy. Some studies therefore considered different phases in their analysis, highlighting that the influence of the different factors was not constant over time. One of the main factors explaining the difference in the number of cases and mortality related to Covid-19 between regions is the delay between the start of the epidemic and the adoption of containment measures (Pierantoni *et al.* 2020).

These six categories of factors are closely intertwined given the systemic and multifaceted nature of epidemic diffusion (Biglieri *et al.* 2020). This systemic nature characterises most urban-related issues, but it is even more so for those related to urban resilience and health (Connolly *et al.* 2021). Air pollution is directly related to urban density, and there are correlations between connectivity and density. Policies adopted by cities were influenced by their global connections, and even the urban infrastructure proved to be somehow elastic over time, as exemplified by the construction in record time of a hospital in Wuhan.

While the systemic nature of the epidemic outbreak is acknowledged by most authors, it is very difficult to account for it through an aggregated statistical model such as those considered in this review. This would require modelling the respective adaptation of different agents through time. In this view, urban density itself may be considered as a variable through time, influenced as it is by working restrictions and residential relocation within cities.

The discussion of the systemic relations between the built environment and Covid-19 diffusion would benefit from being framed in a spatial political ecology perspective. This is due to its transdisciplinary nature, the interplay between the human and non-human factors it mobilises, the technological dimension of test-and-tracing policies adopted in some high-density cities, and the place-based nature of the debate (Connolly *et al.* 2021). Such a prism invites a consideration of how the political economy and the local distribution of power may have hastened the diffusion of the disease, given the conditions of urban density, through neo-liberalisation and privatisation policies (Lam Chung *et al.* 2020). The impact of Covid-19 is indeed exacerbated in those places where health systems are not adapted to face the crisis because of a lack of resources or mismanagement (Gupte & Mitlin 2020).

4. POSSIBLE REASONS OF THE DIVERGENCE: THE EFFECTS OF DENSITY

As noted above, important divergences occur with regard to the possible effect of urban density on the magnitude of the diffusion of Covid-19. These divergences are not uncommon in the scientific debate. Some issues considered below may help to contextualise these divergences.

None of the papers addresses all the factors mentioned above. Only a subset of these is usually considered. This can be explained by a lack of available data when the studies were performed. It is partly related to national differences with regard to access to some data, *e.g.* the flows of travellers between cities. Besides this, the short time frame in which these studies were performed may also explain why some researchers could not access all the data in the required time frame. Most importantly, density and connectivity are not always distinguished by all authors. Even though these are related variables, they are clearly different on a conceptual and statistical basis (Hamidi *et al.* 2020). Some urban settlements may be very dense with very low connectivity, especially external connectivity. The influence of urban density on the diffusion of Covid-19 tends to be reduced or even to be negative in those studies that distinguish both factors (Hamidi *et al.* 2020).

Only a small number of studies consider external connectivity, even though it is widely acknowledged to play a crucial role in the diffusion of diseases in a globalised word (Connolly *et al.* 2021). External connectivity is directly related to the velocity, extensity, intensity and impact propensity of global connections (Ali & Keil 2007). The number of trips that originated from existing Covid-19 clusters appears as one of the main influential factors of propagation in many studies (Qiu *et al.* 2020; Lin *et al.* 2020). Urban density is somehow correlated with external connectivity. The denser and larger cities are usually more connected to other large cities. Ignoring external connectivity as a specific factor may hence lead to overestimations and an overemphasis of the urban density factor (Hamidi *et al.* 2020). Addressing connectivity requires a better control of the 'contact structures of individuals through local and global linkages of personal contacts' (Ali & Keil 2007: 1221). In this view, large, dense cities were not so much the *epicentre* of the pandemic, but at the *vanguard* of the pandemic's front (Angel *et al.* 2020).

There does not appear to be an agreed understanding of urban density in all these papers. In some cases, it is measured by the share of the population living in high-density settlements (Boterman 2020; Angel *et al.* 2020). Most authors refer to gross densities (inhabitants/km^2) rather than net densities (inhabitants/km^2 of urban areas). This later metric is only used by Jamshidi *et al.* (2020). The use of gross density is known to increase the relative weight of larger cities, especially when calculated at the province level, as in Lin *et al.* (2020). This induces a confusion with internal connectivity that is related to the total number of inhabitants in an urban area rather than their relative concentration in space (Hamidi *et al.* 2020). Apart from this, when it is calculated at the country scale, density merely reflects geographical attributes and their degree of urbanisation rather than some specific form of urban organisation.

Important divergences about the dependent variable are apparent in the studies consulted. The dependent variable measuring the incidence of the pandemic at the local level may be the total number of reported cases, the number of reported cases/100,000 inhabitants or the number of reported deaths/100,000 inhabitants. The conclusions may not be the same according to the dependent variable (Angel *et al.* 2020; Hamidi *et al.* 2020). Urban density is associated with better healthcare structure, which reduces the number of deaths/100,000 inhabitants (Hamidi *et al.* 2020). Several studies did not consider the testing/tracing policies adopted in their analyses. This may also influence the observed effect of density, especially when there is more testing and hence more reported cases/inhabitants in urban areas.

In larger cities, the 'urban health penalty', *i.e.* the risks associated with the combination of concentration of disadvantaged groups, increased connectivity and more frequent contacts between individuals may be more than compensated for by an 'urban health advantage'. The advantage is better access to health facilities and better-staffed public health departments (Vlahov *et al.* 2005; Rodwin & Gusmano 2002). Social cohesion and the availability of active community support groups may also play a positive role in dense, diverse urban environments.

The divergence in the results may be further explained by differences in scales of analysis, from the country to urban agglomeration and county level. Analysis at the county level is most appropriate to single out the effect of urban density from the one of external and internal connectivity. Actually, Hamidi *et al.* (2020) highlights that these three variables are not so much correlated when density is measured at the county level. Those studies that were performed at the county level did not include the same set of counties: some focused on urban counties (Hamidi *et al.* 2020), while other studies considered all counties, whether rural or urban (Zhang & Schwartz 2020; Jamshidi *et al.* 2020). Ideally only those counties presenting a sufficient number of cases/deaths should be considered in the analysis, given the high uncertainty related to counties where very cases were reported.

Cross-country comparisons are especially sensitive to the way testing-and-tracing policies were implemented at the national level (Amdaoud *et al.* 2020). The approaches to counting deaths were not consistent from one country to another, especially in the first months of the pandemic when testing was not available for all suspicious cases. None of the cross-country analyses reviewed here explicitly considered this possible bias, and it may have significant effects on the results. The relation to urban density is more difficult to establish in this case, as country divergences in testing procedures do not seem to be systematically related to density. It should be noted that global cities characterised by a high density and a low number of cases per inhabitants, such as Singapore, Seoul (South Korea), Shanghai (China) or Hanoi (Vietnam), were also the most prone to adopt stringent testing-and-tracing policies (Fang & Wahba 2020). The perceived vulnerability of these cities, and their previous experience of the severe acute respiratory syndrome (SARS) outbreak, played in a role in a faster and more widespread reaction.

Finally, some of the divergences observed between studies may be attributable to differences in statistical models. Most studies performed multiple regression analyses, considering either a linear or a non-linear impact of density (Lin *et al.* 2020). Hamidi *et al.* (2020) used structural equation modelling (SE). The added value of SE is that it can address direct and indirect effects, which is a step forward in the direction of considering the systemic nature of the issue. Quantile regression was used to analyse the importance of factors, according to observed quantiles at different weeks from the initial outbreak (Sigler *et al.* 2020). This allowed the authors trace the evolution of the pandemic along the urban hierarchy and the evolution of the weight of factors across time. Urban density then appears as an element that may play a role at some stage of the epidemic, but that progressively fades away once it diffuses along the urban rural gradient (Sigler *et al.* 2020).

5. THE MAIN GAPS IDENTIFIED IN THE LITERATURE

One gap identified so far in the literature is the lack of consideration for possible interactions between the six categories of factors and their consequences on the incidence of the virus. Addressing these relations will never be obvious using aggregate statistical models. Actually, these models limit collinearity which may lead to inadequate conclusions concerning the relations between dependent and explanatory variables. The interactions between direct and indirect factors and the consideration of possible adaptation processes do have a great relevance in a policy-driven perspective. There is a need for highly disaggregated micro-simulation analyses, at the individual level, considering the constraints and preferences of urban agents as well as their evolution through time (Zhang & Schwartz 2020). Micro-simulation models may be informed by psychological experiments on the subjective perception of urban density (Hooper 2018), ideally conducted before and after epidemic outbreaks. These models may help to address possible adaptations related to the preferred transportation modes and working habits. These models can also consider the effects of interpersonal differences rather than mean characteristics at the group scale. Such a shift from aggregated to disaggregated agent-based models is all the more important given the direct mobilisation of firms and individuals in the management and governance of the Covid-19 response (Lam Chung *et al.* 2020).

Urban density is an easily accessible variable, especially when it is defined as the ratio between the number of inhabitants and gross surface area. It can be understood as an integrative measure of the likely clustering of unrelated people in given locations. However, a more sophisticated approach to defining and analysing density is necessary. Density should be calculated dynamically to reflect the actual pulse of the city. Chen *et al.* (2019) proposed a method to assess the 'vibrancy' of a place through the use of social media. Their method allows one to identify dynamic hotspots of users at a 1 km^2 cell resolution. Such measures are directly related to the close person-to-person interactions in some specific places, such as transport hubs, recreational areas, mass public events, *etc.*, and their possible evolution over time. The focus on more specific temporal and locational data would potentially highlight the huge differences of densities and clustering of individuals within a given city, considering both their residential, work and recreative activities. A mean density calculated at the city or provincial scale appears as a far too aggregated indicator to reveal the strength of connectivity and urban flows in the city.

In other terms, different density measures relate to different policy measures. The use of aggregated densities at the city or county scale is not the most relevant metric for measuring the health risks related to person-to-person interactions. More refined metrics, considering the mix of different vulnerability groups at a much finer grain scale, are necessary.

Focusing on urban density somehow nurtures the romantic myth of a 'bounded city', which would be controllable through its intrinsic properties. The experience with Covid-19, and more generally urban health, rather invites one to address the unbounded and topological nature of the contemporary city (Connolly *et al.* 2021), considering the interactions between cities as well as along the urban–rural continuum (Azevedo *et al.* 2020). Studies considering the porosity between urban units highlighted the fact that the effect of density rapidly declines with an increased mixing of spatial units (Whittle & Diaz-Artiles 2020).

A further gap identified in the literature is related to the lack of consideration for interactions between urban scales. Until now, most studies regarding urban density are developed at the agglomeration or provincial level. Overcrowding and density would better be addressed at the building level, and related to residential or work activities (Florida 2020; Pierantoni *et al.* 2020). The SARS outbreak was related to transmission within hospitals (Ali & Keil 2007) and some residential buildings. The Amoy Gardens residential buildings had transmission through the plumbing system (McKinney *et al.* 2006). Retirement facilities somehow played a similar accelerating role with regard to Covid-19 (Biglieri *et al.* 2020). Big data analysis of mobile location in US metropolitan areas highlights that the transmission of the virus is directly related to the clustering of people in specific places, *e.g.* restaurants, fitness clubs, hotels, workplaces or retail (Chang *et al.* 2020). McPheasron *et al.* (2020) highlight that the percentage of death from Covid-19 in New York is significantly and positively correlated with crowded homes. Following the recommendation of the Centers for Disease Control and Prevention (CDC) (Flanagan *et al.* 2011), crowded homes are defined in the US as dwellings with more than one occupant per living space (not including bathrooms or most kitchens). This factor is especially important in the case of multi-generational dwellings, where asymptomatic individuals may interact with highly vulnerable ones.

An increased attention to construction techniques and operation systems, *e.g.* indoor ventilation, heating, ventilation and air-conditioning (HVAC) system or the cleaning of buildings (Pinheiro & Luís 2020), are important factors. In addition, an improved building resilience requires adequate forms of design in order to cope with the increased density related to a more diverse use of the space, where eating, working, recreation and studying tend to overlap (Keenan 2020; Lam Chung *et al.* 2020). The entrance of buildings may have to be rethought in order to provide more space for discarding clothing and doing washing (Pinheiro & Luís 2020), and the presence of rooms for self-isolation is required in dense, packed housing, as exemplified in the case of student housing. In any case, the epidemic outbreak dramatically revealed the 'significance of home in healthcare', and by contrast the fragility of the homeless (Lam Chung *et al.* 2020).

A concentration of vulnerable individuals within buildings acting as concentration hubs will always be critical for the diffusion and incidence of the disease. Certain facilities, *e.g.* collective social housing, prisons, health facilities and retirement homes, are increasingly located on the periphery of larger cities, in low- or medium-density areas (Biglieri *et al.* 2020). Several policies have been adopted to reduce transmission chains in these nodes over time, especially in their common (shared) areas. Again, urban density indicators at the agglomeration or higher scale fail to engage with the challenges and issues faced at the building level and their likely consequences in terms of resilience and sustainability.

More attention needs to be dedicated to the interplay between preventive and adaptative measures, and especially long-term, structural adaptations. Very few papers address the opportunities seized by cities during the Covid-19 crisis, even though the early adoption of coping strategies with regard to active mobility, community engagement and housing protection were substantial in some cities (Sharifi & Khavarian-Garmsir 2020; Keenan 2020; Gupte & Mitlin 2020). Such adaptation measures may be developed more rapidly in dense environments, with more human and knowledge capital to bounce back after the stress. As stated by Reyes *et al.* (2013: 141):

> urban centers pose great challenges in terms of disease, but they also present unique opportunities for health promotion and disease prevention.

A better consideration for measures adopted by cities during the Covid-19 crisis may unveil the conditions for a collective rethinking of services required by urban density at both the local and metropolitan scales. Housing regulations certainly need to be adapted to the potentialities and risks associated with an increased diversity of functions. Without a due reflection on the required and observed adaptations, there is a risk that the Covid-19 crisis leads to an 'ossification of pre-existing inequalities and structural failures' (Gupte & Mitlin 2020: 13).

Generally, divergences in governance styles and structures are still poorly addressed in present statistical models, even though they play a critical role in the regulation of activities, accessibility of healthcare and mobilisation of resources (Connolly *et al.* 2021; Amdaoud *et al.* 2020). The 'grid governance' scheme partitioning the city into various small grids very likely helped the Chinese authorities face the exponential growth of the pandemic through a combination of state-based community support and control function at the level of district, street and residential communities (Lam Chung *et al.* 2020). The digital turn, including here both dataveillance through track-and-tracing applications and its opposite, *i.e.* community empowerment through more informed access to decentralised data infrastructure, is to be framed in a political perspective, considering its lasting influence on the relations between people, the community, government and the urban environment.

The issue of how to live with the pandemic in dense urban settlements is of prime importance. Better access to the internet and home-service delivery may have helped inhabitants of denser cities to comply with stay-at-home restrictions, adopt more precautionary behaviours and avoid unnecessary contact (Fang & Wahba 2020, Hamidi *et al.* 2020). The accessibility to green infrastructures and other urban amenities did somehow compensate for stringent stay-at-home measures (Pierantoni *et al.* 2020).

The initial outbreak in Italy concentrated in the in-between urban landscape of Bergamo, characterised by a network of small cities, sub-urban constellations and rural municipalities. The combination of a high external connectivity and deficient healthcare services in this 'extended urbanization' landscape contributed to the magnitude of the outbreak and its consequences (Biglieri *et al.* 2020). There is a need for more research on the global urban periphery: the peri-urban places characterised by close contact between urban and natural environments (Connolly *et al.* 2021).

Some 25% of the world's urban population lives in informal settlements (UN 2018). The health risk is extremely acute in these areas, *i.e.* 'forgotten densities' associated with an increased vulnerability to Covid-19 due to overcrowding and living conditions (Biglieri *et al.* 2020; Neiderud 2015). In many cases:

> density itself is not the problem; it is the overcrowding that is a result of poverty and the lack of infrastructure and service from state neglect.
>
> (Gupte & Mitlin 2020: 9)

The resources for quarantining and sanitising are almost non-existent in these areas. Part of the economy is dependent on street vending and informal activities, which were sometimes abruptly cancelled from one day to the next, without state support for the urban poor who suffered from these restrictions. Social distancing is often a luxury or impossibility. Inhabitants have no other choice than maintaining economic and social activities despite the risk of contracting or communicating the disease (Gupte & Mitlin 2020). Technology-based responses are not operating in these urban environments, given the inequality of access to digital infrastructures in the Global South, especially between men and women. Community monitoring appears as a much more adapted solution to collect evidence about the progress of the disease and provide accurate information to inhabitants.

Adaptation measures adopted to address Covid-19 may have a larger impact on urban resilience. The case of stay-at-home policies implies an adaptation of home environments and may prove beneficial during climate or safety events. Considering the vulnerability to health risks in the wider landscape of urban resilience would help cities, citizens and companies to adopt measures that may be beneficial in a future crisis. This is especially important as this is probably not the last public health emergency our cities will face (Acuto 2020). With regard to the built environment, priority should be given to those measures, as, for instance, reducing air pollution, that not only contribute to risk reduction but also promote urban sustainability, possibly in a disruptive perspective (Pinheiro & Luís 2020).

6. CONCLUSIONS

Existing studies related to the impact of urban density on the incidence of Covid-19 were reviewed in this paper. Despite the intuitive impression that there should be a strong correlation between both variables, scientific articles published so far indicate that it is a complex and disputed issue. The divergence between studies may be attributed to several factors, amongst which are the type of variables considered, the definition of urban density, the variable used to measure Covid-19 incidence and the statistical models.

Most importantly this review highlights the importance of disentangling urban density from internal and external connectivities. These three variables may be intertwined, but they are nonetheless different on a conceptual level. More importantly, they are related to different types of measures and policies. Although urban density is a very easily accessible variable, it is also a very aggregated one and therefore may conceal more than it reveals in terms of chains of transmission. More efforts are needed to provide dynamic spatio-temporal measures of urban density and across a variety of scales, from the building to the agglomeration level. This could help to direct efforts and restrictions in the most appropriate places (Chang *et al.* 2020). The lasting urban impacts of the Covid-19 crisis may not be related to urban density. Instead, there are likely to be disruptions in connectivity, especially in those 'relational cities' that are most dependent on intermediary services and global exchanges (Hesse & Rafferty 2020).

More research has to be directed towards interactions between factors, between urban scales, and between prevention and adaptation measures. This will require more qualitative research in order to better understand the evolution of these interactions over time (Gupte & Mitlin 2020). Qualitative research related to everyday interactions with the virus in dense urban environments is very important in the Global South, characterised by a lack of accurate up-to-date data. It is also essential in data-rich environments to calibrate and validate micro-simulation models that could grasp the adaptive nature of urban health systems.

A growing body of evidence exists on the health benefits of lively, active, dense urban environments, especially through walkability (Wang & Yang 2019; Hamidi *et al.* 2020). There is a risk that the present 'covidisation' of research (and its funding) may neglect other important challenges that deserve much attention, *e.g.* public health or sustainability.

The relation between urban density and health issues should be framed in a vulnerability perspective, considering the interplay between exposure, sensitivity and the adaptive capacity of cities. Covid-19 has been assimilated to a form of 'forced experimentation' by some authors (Acuto 2020), promoting rapid solutions that could lead to transformational adaptations, *i.e.* non-linear interventions that reorder and/or relocate systems, transform places and shift locations in a structural way (Kates *et al.* 2012). In some weeks, data have been aggregated in public open-source data repositories. New tracing applications have been tested, adopted and sometimes rejected. Local 'resilience hubs' flourished in some cities for deploying public health, the delivery of food or maintaining social contacts with isolated persons (Keenan 2020). Those cities that will be able to best learn and capitalise not only *from* but also *while in* this experience will be better prepared for a future health crisis (Acuto 2020; Keenan 2020). They may take a decisive advantage in terms of governance and community-based decision-making.

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