BUILDINGS & CITIES

Pandemics and the built environment: A human–building interaction typology

RESEARCH

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ABSTRACT

Surveys of urban history from ancient times to the present reveal a continuum of collective responses to pandemics ranging from quarantine facilities and monitoring the spread of disease to building new wastewater networks. The contemporary COVID-19 pandemic includes new digital tools and techniques that supplement (and sometimes replace) the existing analogue responses, while raising new ethical issues with respect to privacy. A typology of pandemic responses in cities is created, based on human–building interaction (HBI) principles. This typology can be used to compare and contrast analogue and digital responses relating to distancing, monitoring and sanitising. It provides a summary of a wide range of individual and collective implications of pandemics and demonstrates the indelible connections between pandemics and the built environment. In addition, the typology provides a tool to interpret some of the opportunities and drawbacks of digitalising cities.

PRACTICE RELEVANCE

The COVID-19 pandemic has demonstrated the enduring co-evolution of cities and disease through history. This study aims to inform future pandemic preparedness by providing a framework for designers, managers and users of public spaces to evaluate the multiple implications of emerging technologies that are integrated within the urban fabric. While the rapid rise of digitalisation to advance urban health agendas continues to raise new questions relating to individual and civic freedoms, HBI qualitatively provides a lens through which to examine the overlapping spatial, ethical, and temporal consequences for humans and the built environment. Urban planning researchers and designers can use HBI principles to humanise the sustainable smart city.

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1. INTRODUCTION

COVID-19 has had widespread impacts on communities around the world. These impacts are particularly visible in cities where a combination of historical and emerging public health actions have been implemented to minimise the transmission of the disease between individuals and groups (Lee *et al*. 2020). Buildings, streets and public spaces provide a dynamic interface between human populations and disease vectors (Biglieri *et al*. 2021; Lai *et al*. 2020; Sharifi & Khavarian-Garmsir 2020; Vargo *et al*. 2021). Urban stakeholders, including local, regional and national governments, private companies, and residents, have implemented a range of analogue and digital responses to slow the spread of pathogens (Budd *et al*. 2020; Ting *et al*. 2020; Vargo *et al*. 2021; Whitelaw *et al*. 2020). The aim of this paper is to compare and contrast these responses to reveal the sociospatial implications of pandemics and the various ways that humans reconfigure their relationships to the built environment to address public health issues.

Human–building interaction (HBI) principles recognise that humans and buildings are in a constant state of co-evolution and provide a useful lens to interrogate the spatial implications of pandemics in cities (Alavi *et al*. 2019b; Kirsh 2019; Schnädelbach 2016; Urquhart *et al*. 2019). The introduction of information and communications technology (ICT) contributes to these transformations while introducing new issues related to transparency, trust and ethics (Alavi *et al*. 2019a, 2019b). The emergence and development of HBI principles have been informed by preceding transdisciplinary discourses concerning ubiquitous computing, pervasive computing and ambient computing (Schnädelbach & Kirk 2019; Shepard 2011; Weiser 1991). A core design challenge has now arisen through a shift of scale from objects and interactables to spatial and public settings (Dalton *et al*. 2016b; Moradi *et al*. 2018; Wiberg 2017). Urban public vulnerability is heightened as digital technologies become increasingly embedded in our urban environments (Fahey & Hino 2020). However, there is a scarcity of scholarly discourse examining the sociospatial implications of these changes.

This study employs HBI principles to assess a typology of analogue and digital pandemic responses in cities, and the range of individual and collective implications of pandemics to demonstrate the indelible connections between urban development, pandemics and the built environment. In addition, the typology provides a tool to interpret some of the opportunities and drawbacks of digitalising cities.

The remainder of the paper is structured as follows. It begins with an overview of HBI and its utility in analysing pandemic responses in cities by focusing on three HBI principles: (1) changes in use; (2) personal consent and public access; and (3) permanence. These principles are then applied to the pandemic responses of distancing, monitoring and sanitising to demonstrate the similarities and differences between analogue and digital responses. The paper concludes with a summary of the typology and suggestions for future research.

2. BACKGROUND

Public health crises are not a new phenomenon, and urban centres have continuously evolved to cope with such situations (Lee *et al*. 2020). The COVID-19 pandemic has again brought architectural and urban planning considerations to the forefront of the current public health discourse, where key concerns include addressing issues such as overcrowding, homelessness, usability of spaces, provision of greenspace, in addition to access to essential public services such as transportation, water and wastewater, and healthcare (Biglieri *et al*. 2021). The application of ICT to the built environment introduces a digital dimension to existing physical infrastructure networks. Examples include travel cordoning via the provision of vaccination 'passes', urban surveillance using biometric wearables and wastewater-based epidemiology, and smart sanitation solutions (Budd *et al*. 2020; Daughton 2020; Rary *et al*. 2020; Ting *et al*. 2020). HBI serves as a useful conceptual lens through which to study the contemporary phenomenon of pandemics in cities (Alavi *et al*. 2019a).

Where human–computer interaction (HCI) emphasises the relationship between humans and various forms of computing (mobile, ambient, tangible, ubiquitous and pervasive), HBI focuses on the built environment as another key factor in the interaction between the human and the digital.

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It recognises that buildings, public spaces, infrastructure networks and other physical artefacts are unavoidably implicated in new human–digital configurations (Alavi *et al.* 2019a). Transitions from artefacts to environments are informed by concepts from HBI and related fields to encompass the complexity of social experiences with and within built environments (Alavi *et al.* 2019a). This draws our attention to the social, cultural and historical characteristics that are implicated in the wellbeing of urban residents (Wiberg 2011; Sengers & Peine 2021). HBI research also offers an emerging discourse that acknowledges the centrality of context and place in the application of digital technologies (Bell & Dourish 2007; Boer *et al.* 2015; Dalton *et al.* 2016b; Luck 2016: 37–52; Mitchell & Raudaskoski 2013; Schnädelbach & Kirk 2019; Vallgarda 2014).

HBI provides concepts to examine the interactions between humans, digital technologies and the built environment. Specifically, the principles of 'changes in use', 'personal consent and public access' and 'permanence' provide a framework to analyse the wide range of implications of pandemic responses in cities (Schnädelbach *et al.* 2019) (Figure 1). These principles are summarised briefly below along with examples of historical and contemporary analogue and digital pandemic responses.

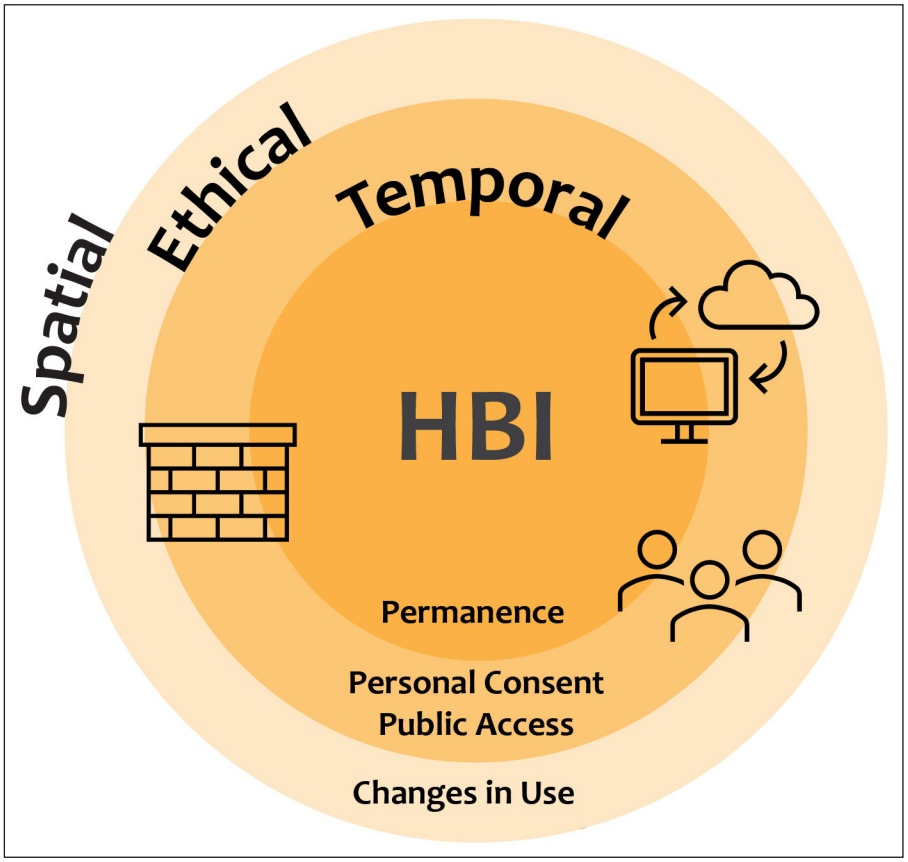

Figure 1 The human–building interaction (HBI) principles of permanence, personal consent and public access, and changes in use.

Source: Adapted from Alavi *et al.* (2019b).

2.1 CHANGES IN USE

The HBI principle 'changes in use' addresses the link between ICT and building adaptivity (Schnädelbach *et al.* 2019). The integration of digital technologies within the built environment facilitates repurposing of existing spaces as well as the creation of completely new infrastructures and building uses to address the needs of different user groups. This can result in significant changes to existing patterns of circulation and movement and has substantial implications to the form and function of the built environment and user experiences (Schnädelbach *et al.* 2019). Examples of such 'architectural adaptivity' include opening or closing access routes through a given building or provision of personalised spaces depending on a user's physiological or psychological needs, as well as the introduction of automated doors, elevators, escalators, and adaptive lighting and ventilation (Becerik-Gerber *et al.* 2022; Dongre *et al.* 2021; Schnädelbach *et al.* 2019). In all cases, spatial changes in the built environment are used to accommodate changes in use.

2.2 PERSONAL CONSENT AND PUBLIC ACCESS

The digitalised built environment provides multiple opportunities to collect data from urban residents to create a layer of digital information that complements the analogue built environment (Clements-Croome 2011; Kumar *et al.* 2018; Mofidi & Akbari 2020; Sharples *et al.* 1999). This data layer is used to manage urban processes such as transportation, water and energy provision more effectively, and has been observed through the increasing application of digital twin and blockchain technologies within the building industry (Davila Delgado & Oyedele 2021; Li *et al.* 2019). The HBI principle of 'personal consent and public access' problematises this relationship between individual data and the built environment. Specific concerns may include whether consent is required and the benefits and drawbacks to individuals who can or cannot provide their personal data (Genestier *et al.* 2017; Nanni *et al.* 2021). Examples include sensing environments that feature facial recognition using CCTV footage, automated number plate recognition and voice recognition (Dalton *et al.* 2016a, 2016b; Schnädelbach *et al.* 2019; Schnädelbach & Jäger 2019; Schnädelbach & Kirk 2019).

2.3 PERMANENCE

The HBI principle of 'permanence' emphasises the temporality of buildings as well as the short- and long-term collection, storage, and transfer of personal data made possible by analogue, digital and hybrid urban environments (Schnädelbach *et al.* 2019). It is related to the Vitruvian architectural tenet of *firmitas* (also referred to as 'firmness') and problematises the temporal implications of embedding digital technologies within the existing physical building fabric (Vitruvius/Rowland & Howe 1999). Long-term data management can alter the relationship between humans and the built environment in multiple ways. Schnädelbach *et al.* (2019) point to ancient Egyptian hieroglyphics as one of the earliest instances where stories and information relating to individuals and groups were inscribed in the built form (Schnädelbach *et al.* 2019). Contemporary data-gathering practices can contribute to a ubiquitous environment of geo-surveillance with little accountability to urban residents (Radil *et al.* 2021; Saran *et al.* 2020).

The above three principles comprise conceptual tools to examine how digitalisation is impacting user-to-user and user-to-building interactions in the built environment with respect to space, ethics and time (Table 1). With respect to pandemic responses, these principles help to emphasise the connections between the built environment and ICT while revealing the opportunities and drawbacks of various strategies to enhance public health by limiting the spread of disease.

Table 1 Summary of human–building interaction (HBI) principles and pandemic responses in cities.

HBI PRINCIPLE	DESCRIPTION	GENERIC EXAMPLES
Changes in use	Relationship between information and communication technology (ICT) and building adaptivity (building reuse; creation of new infrastructures and building uses)	Automated doors, elevators, escalators, adaptive lighting and ventilation (smart windows)
Personal consent and public access	Relationship between individual, personal data and the built environment (provision of personal consent to personal data)	Building sensors: facial recognition via CCTV footage, automated number plate recognition, voice recognition, smart thermostats; gathering and applying public census data
Permanence	Short- and long-term implications of personal data collection, storage, transfer within the analogue, digital and hybrid built environments; long-term geosurveillance	Relative life cycle of buildings and building components: Ancient Egyptian pyramids and surviving hieroglyphics versus contemporary sensing environments and buildings with 60–120-year life spans coupled with data management frameworks such as General Data Protection Regulation 2016 (GDPR)

3. METHODS

To apply the HBI framework, a systematic review of academic publications (peer-reviewed articles, books and book chapters) was performed according to the principles described by Petticrew & Roberts (2006). Narratives of historical and contemporary responses to pandemics and the built environment

were identified by analysing sources across architecture and urban planning, public health, urban geography, human–building interaction, and digitalisation and smart cities. The Google Scholar repository was queried by using sets of keyword searches including 'disease', 'pandemic', 'architecture', 'cities', 'built environment', 'urban', 'public health', 'digital', 'covid-19' and 'smart technology'. The searches were conducted between April 2021 and April 2022, and were filtered to include English-language publications between 2020 and 2022. The initial queries resulted in a list of 696 potentially relevant publications. A purposive sampling approach based on the relevancy of titles and abstracts was then applied to select 40 publications for qualitative analysis using the HBI principles.

4. RESULTS AND DISCUSSION

Urban stakeholders have attempted to address the spread of disease in human settlements in multiple ways. The method described above resulted in three thematic categories of pandemic response: distancing and separation, monitoring and tracing, and sanitising and cleansing. These responses are presented below and are connected to the HBI principles of changes in use, personal consent and public access, and permanence.

4.1 DISTANCING AND SEPARATING

Physical distancing and separating are some of the oldest and most applied public health responses to curtail the transmission of disease (Conti 2017; Thu *et al.* 2020). Distancing is a deliberate spatial strategy of disease management that raises challenges in densely populated built environments such as cities. Beyond physical interventions, distancing can be achieved through changes in behaviour such as home isolation and travel restrictions (Conti 2017). Analogue distancing includes the construction of physical premises to house ill citizens, while digitalised distancing measures include vaccination passes and travel cordoning (Walkowiak *et al.* 2021). In all cases, there is an explicit attempt by health authorities to management disease transmission through spatial interventions.

4.1.1 Changes in use

Distancing and separating often involves highly visible changes in use to the built environment. It creates intentional zones of disease and absence of disease by acknowledging that disease transmission is closely related to physical proximity. Physical distancing is 'the practice of staying 6 feet away from others to avoid catching a disease such as Covid-19', whereas social distancing is understood as 'staying home and away from others as much as possible [...]' (Maragakis 2020: n.p.). Self-quarantine involves staying at home, avoiding inviting visitors or sharing household items such as towels, maintaining at least 6 feet of distance from others in the household, and regular hand-washing. Quarantine practices originated in the 14th century and derived from the Italian term *quaranta*, referring to the separation of 'people, animals, and goods that may have been exposed to a contagious disease' (Tognotti 2013: 254). Urban and architectural typologies were later designed to house the sick and took the form of *lazaretto* (also *Nazaretheum* or *Lazaretheum*) for travellers that prevented free movement (Linkov *et al.* 2014; Tognotti 2013). The rise of middle-class suburbs in England during the Industrial Revolution was a response by urban populations to escape the diseased urban conditions with high population densities (Akatsu 2015; Melosi 1999), while Ebenezer Howard's famed Garden City model at the turn of the 20th century prescribed adequate space to quell the spread of disease (Howard 1902). Quarantining and physical distancing continues to be a popular strategy in the COVID-19 era (Ferreira *et al.* 2021; Piguillem & Shi 2022). In addition to Perspex screens and floor stickers, temporary responses include signage that encourages people to maintain a 2 m distance, as well as special hospital areas and home quarantining recommendations and requirements (Speake & Pentaraki 2022). Distancing involving working from home and video conferencing has rapidly emerged as a normal mode of human interaction (Maragakis 2020).

Analogue and digital measures can reduce international disease transmission but can result in unintended segregation and isolation of marginalised groups (Tomes 2010; White 2020). For example, Samuel Kelton Roberts Jr described the racialised history of public health responses that

prevailed in the US city of Baltimore during the tuberculosis epidemic in the 1800s–1900s where early 'spot maps' were used as a form of social geography and racial segregation was practiced at sanatoria (Tomes 2010). Meanwhile, there is a long history of racial and social inequality related to infectious disease in urban centres, ranging from tuberculosis in earlier times to more recent outbreaks of HIV/AIDS and SARS (Keil 2011). Ancient urban practices of gathering in large public places have evolved as the built environment is increasingly augmented with new technologies allow for hybridised interactions, restrictions, and collaborations across physical and digital spheres (Salama 2020). As new patterns of movement and engagement within public space occur, social interactions take new formats that are intended to enhance public wellbeing, but can equally create or reinforce stigmatisation of individuals and groups, acknowledging those with lesser access to the digital tools and knowledge to use them (such as the elderly and poor) (Cilliers *et al.* 2021).

4.1.2 Personal consent and public access

Practices of physical distancing through enforced isolation in homes and purpose-built facilities, along with border controls and national cordoning and vaccination entry restrictions managed by digital technologies, have resulted in growing tensions related to personal consent when implementing these measures. Public access is subject to individual compliance with government-imposed requirements. However, local shifts of quarantine philosophy were evident during the COVID-19 pandemic in Australia with respect to two types of quarantine policies: border controls and social distancing (Moloney 2020). This included the closure of public spaces, ranging from international and domestic sporting events which played without fans before full cancellation, along with cinemas, national parks and recreational facilities. These are vivid examples of how separating and distancing has explicit implications to public access (Moloney 2020).

4.1.3 Permanence

Physical distancing and separation responses have multiple temporal implications to future urban development, borne by specific urban planning paradigms aimed at long-term disease reduction, purpose-built healthcare facilities and vaccination travel requirements. Physical and regulatory interventions vary in their degree of permanence while the effects on the social interactions between individuals and groups might last longer than originally intended. Local and national governance plays a central role in prescribing appropriate levels of separation within urban populations during pandemics (Maragakis 2020; Moloney 2020; Piguillem & Shi 2022; Thu *et al.* 2020). Purpose-built hospitals and healthcare facilities provide permanent separation while many distancing strategies operate on a temporary basis such as public facility closure, event cancellation, and installation of physical barriers and signage. Long-term sociospatial implications can arise where urban citizens may choose to maintain previous physical distances while in public places, hence requiring more space to be designed within indoor public settings such as restaurants or cinemas (Maragakis 2020; Moloney 2020; Piguillem & Shi 2022; Thu *et al.* 2020).

4.2 MONITORING AND TRACING

A second pandemic response involves monitoring and tracing the spread of disease. One of the most celebrated examples of disease monitoring in cities involved the physician John Snow and his attempts to quell the spread of cholera in 19th-century London (Tulchinsky 2018). Snow traced the disease by cross-referencing cholera cases with particular public water wells in the city and identified the contaminated well, giving birth to the modern field of epidemiology. This highlights the metabolic flows of people, natural resources, capital and disease as inherent characteristics of cities. The contemporary 'age of biometric surveillance' offers datapoints that quantify user characteristics and behaviours through monitoring of physical movement and health in real time. Biometric electronic technologies or wearables are:

> computing devices that are worn on our person, characteristically enabling continuous data collection, transmission, recording, analysis, and potentially, sharing.
>
> (Gross *et al.* 2020: 4)

Examples such as smart thermometers and heart rate monitors track vital signs including body temperature, heart rate, blood pressure, blood oxygen saturation and respiratory rate. Meanwhile, helmets and proximity tracing devices are used in airports to measure individual body temperature, crowd-monitoring for temperature, geolocation, tracking of travellers upon entry to a given country, and physical distance monitoring to inform healthcare authorities (Jahmunah *et al.* 2021; Manta *et al.* 2020). Temporary forms of disease monitoring include over-the-counter rapid antigen home testing kits and polymerase chain reaction (PCR) testing at designated health facilities.

4.2.1 Changes in use

Monitoring and tracing strategies create a complementary information landscape to the existing physical built environment. A plethora of digital technologies are being used to enhance practices of monitoring and tracing, via small sensors on the individual or at key gateways of disease transmission to generate static or dynamic maps of disease movement. For example, automated counters at store entrances inform visitors of how many customers are currently in the store and if it is at a level that is deemed to be safe (Khoumeri *et al.* 2021; Petrović & Kocić 2022). Continued access and use of public urban spaces is possible during pandemics through the implementation and uptake of physical–digital hybrid distancing (*i.e.* digital leashes, smart identification and CCTV footage). Similar monitoring is used in public transportation to generate data on estimated or actual users to indicate the level of activity and, thus, potential for disease transmission (Goscé & Johansson 2018; Santiago 2020). In some cases, monitoring and tracing requires physical space such as carparks, schools and community hubs to conduct mass testing and to provide vaccinations. Meanwhile, existing sanitation systems are being retrofitted with monitoring devices as exemplified by the emerging practice of wastewater-based epidemiology (WBE) (Daughton 2020; Mao *et al.* 2020; Randazzo *et al.* 2020). WBE practitioners trace and monitor the presence of pathogens through faecal–oral transmission in urban populations. Advantages include reduction in time delays between infection and hospital admission, as compared with conventional, individual sampling and testing or 'syndromic' methods.

4.2.2 Personal consent and public access

Where distancing and separating is intended to reduce the mobility of disease, monitoring and tracing characterises the circulation of people and diseases across a city and over time. Monitoring technologies can enable greater flexibility in the management of diseases when compared with quarantine practices and can facilitate a greater degree of access to public spaces. However, monitoring practices, whether analogue or digital, inevitably include issues of personal consent and public access since they involve the collection of personal and collective data to manage urban metabolisms. The COVID-19 pandemic highlighted how the collection of personal data through a wide range of digital surveillance mechanisms resulted in the loss of civil liberties and a lack of citizen input and consent (Kitchin 2020; Sharma & Bashir 2020; Whitelaw *et al.* 2020). Digital technologies such as thermal screening and digital contact tracing have also been used to gauge community transmission but introduce important privacy and civil liberty issues.

Of particular concern is the normalisation of individual surveillance, and the rise of 'control creep' where data collected for public health monitoring are then used for other purposes (*e.g.* locating suspected criminals) (Ometov *et al.* 2021). The monitoring of disease and other individual biometrics raises questions about the politics and power of harvesting individual health data to inform public health agendas. For example, current WBE methods are not precise enough to identify specific individuals and locations when compared with clinical testing (Daughton 2020). Nevertheless, emergency response teams can be alerted to infections present in towns, cities, drainage areas, and at the scale of neighbourhoods and building complexes. Whereas population size can decrease sample sensitivity, subgroup sampling within cities has the potential to stigmatise vulnerable communities (Daughton 2020). The ethical and privacy considerations of digital monitoring were raised a decade ago while the COVID-19 pandemic introduced an interconnected 'digital ecosystem' with both positive and negative implications (Ting *et al.* 2020; Wiberg 2011). Kitchin (2020) specifically queries the capacity of surveillance technologies to balance civil liberties and effective public health responses. Designing to enhance interactional choices for all groups can constitute a core criterion (Schnädelbach *et al.* 2019).

4.2.3 Permanence

With monitoring and tracing, permanent changes or adaptations to the existing built environment are less common. However the possibility of long-term and widespread geo-surveillance can be an unintended consequence of monitoring and tracing the outbreak of diseases. Surveillance technologies have enabled some liberties in movement while also raising questions about the long-term, permanent storage of the collected personal data (Kitchin 2020). Whereas wearables are designed to be removed after a period of time, the datastreams produced by monitoring devices can be stored indefinitely and result in the normalisation of state surveillance.

A notable departure from historical, analogue urban sanitary infrastructures arises through the collection of human waste materials for the purpose of scientific analysis, made possible by digital technologies. 'Smart sanitation' and wastewater epidemiology are being developed to improve the monitoring of individual and community health with respect to diagnostics and disease surveillance. This includes the use of biosensors to monitor behaviours such as toilet usage and urine flow, in addition to applications at industrial wastewater treatment facilities and potable water systems (Daughton 2020; Randazzo *et al.* 2020; Rary *et al.* 2020). In particular, 'smart toilets' are defined by Rary et al. (2020: 4) as:

> self-contained and autonomous tools that analyze the user's urine and faeces for personalized health monitoring in real time.

Hence, autonomous biosensor technologies are emerging as an integral feature of sanitary infrastructure networks (Santiago 2020). ICT has the potential to transform sanitation infrastructure into a diagnostic tool for disease identification and monitoring, but also for the detection of cancer, use of illicit substances, monitoring of individual health parameters, *etc.* Surveillance technologies create a ubiquitous and permanent monitoring infrastructure in cities that is quickly becoming a normalised condition (Sutherland & Cook 2017; Bibri 2021).

4.3 SANITISING AND CLEANSING

Where distancing and separating involves physical interventions in disease transmission, and monitoring and tracing involves following and characterising disease transmission, a third theme of pandemics in cities involves sanitising and cleansing to remove diseases. Hygiene and sanitation practices have played a central role in the reducing the spread of disease throughout history and continue to be influential in the COVID-19 era (Hannah *et al.* 2020; Howard *et al.* 2020; Lai *et al.* 2020; Martínez & Short 2021; Piret & Boivin 2021). Ongoing initiatives such as water, sanitation and hygiene (WASH) conducted by the Stockholm International Water Institute (SIWI) and United Nations Children's Fund (UNICEF) demonstrate the importance of sufficient public sanitation services to support the wellbeing of urban populations (Giné-Garriga *et al.* 2021). Safe and secure access and use of handwashing soap and hand sanitiser along with running water are vital components of this practice (Donde *et al.* 2021; Giné-Garriga *et al.* 2021). The historical development and recent digitalisation of public sanitary infrastructure is central to the management of pandemics.

4.3.1 Changes in use

The historical record exhibits many physical changes to buildings, streets, and public places to facilitate improved sanitation and cleansing. Ancient traditions of city-building were characterised by the construction of large-scale, ambitious public sanitary infrastructure networks to serve increasingly dense populations. New architectural typologies came into existence and cities played various roles to enhance the health and wellbeing of urban residents. Early examples of community-scale sanitation include the Mesopotamian Empire (3500–2500 BCE) and the settlements at Harappa and Mohenjo-Daro in the Indus River Valley Civilization where heavy monsoons and flooding drove the development of urban hydrological infrastructures that separated sewage from drinking water (Ingersoll & Kostof 2013). Increased urbanisation during the 19th century led to increased threats of disease to large swathes of the working population, and prompted the development of public sanitation services. The pivotal 19th-century advances of sanitation practices in Europe and North America also serve as examples of new architectural and urban typologies, through the construction

of early protosystems, waterworks for filtration and treatment, and Sir Joseph Bazalgette's design of London's first sewer network that continue to serve as the foundation of current infrastructure networks (Collinson 2019; Melosi 1999). Paramount was the theory of disease transmission, later known as the germ theory of disease conceived from the idea that 'bad' air and water were in part responsible for causing sickness and linked to relevant environmental conditions such as water supply (Kiechle 2021; Ma & Sheetz 2017). Historians acknowledge these undertakings as being responsible for eradicating cholera outbreaks in the city (Melosi 1999). In the contemporary era, the emergence of manual and automatic hand sanitiser dispensers served as a proactive way for urban residents to prevent the spread of COVID-19. Public authorities used signage to reinforce the need for regular handwashing, using simple techniques to effectively remove bacteria (Gwenzi 2021; Hannah *et al.* 2020; Howard *et al.* 2020). This was complemented by more frequent and deep cleaning of public transportation, spaces and surfaces, despite varied scientific opinion on the efficacy in quelling airborne viruses (Lewis 2021).

4.3.2 Personal consent and public access

Throughout human history, individual physical cleanliness and the cleanliness of one's surroundings have become cornerstones of civilised societies, and the provision of related public services indicates a functioning state with a commitment to public health (Ingersoll & Kostof 2013). Challenges arise where these services are less accessible, and discrepancies in strategy emerge across urban settings in the Global North and South (Donde *et al.* 2021). Inadequate supply and unstable access to sanitation facilities generates unsafe public urban spaces and increasing risk of disease for urban populations, especially women and those from lower socio-economic status (Giné-Garriga *et al.* 2021). In contrast to the public urban responses of distancing and separating and monitoring and tracing, the tensions between personal consent and public access to sanitising manifest in different ways. Universal access to a sanitary urban environment emerges as a human right and this requires greater public access to water, sanitation and hygiene infrastructures (UN 2022). It also requires personal consent and public adherence to sanitation governance protocols. The previous discussion on WBE noted that sanitary infrastructures are not only used to remove disease from cities but also to track how diseases travel through urban populations. Hence, a dual combination of monitoring and sanitising is apparent in pandemic responses. Unlike the ancient and late modern era predecessors, current and future practices of WBE may embody significant tangible and intangible implications for the use, access, and experience of urban sanitation facilities.

4.3.3 Permanence

Sanitation infrastructures and facilities are a permanent feature of contemporary urban centres that embed the ethos of public sanitation into the built form (Ingersoll & Kostof 2013). Whereas history demonstrates physical and enduring construction of urban sanitation typologies, many COVID-19 strategies for urban sanitation are more ephemeral in character. Hand-sanitiser dispensers, frequent cleaning of public spaces and surfaces, and by more rigorous personal hygiene practices such as handwashing are likely to decrease as the pandemic subsides. Meanwhile, the rise of smart sanitation movements has the potential to add another dimension to the daily and long-term operation of urban sanitation infrastructures, whereby such systems can also serve as conduits of information and surveillance of the physiological health of urban populations. Built sanitation interventions are costly, require long-term planning and financing for construction and long-term maintenance (usually by a public authority). The rise of COVID-19 provides an opportunity to revisit the sanitary city dialogues of the 19th century while also reinforcing the need to improve sanitary conditions in both the Global North and South.

4.4 LIMITATIONS AND FUTURE APPLICATIONS OF HBI

This article demonstrates the utility of using HBI principles to analyse the implications of pandemics on the built environment. However, it is also important to reflect on the limitations of such an approach, specifically with respect to urban digital transformations. Clements-Croome (2011) and Preist *et al.* (2016) criticise the significant environmental impacts of digitised infrastructures

and current user-centred design paradigms, using the lens of sustainable intelligent buildings and sustainable interaction design (Clements-Croome 2011; Preist *et al.* 2016). Whereas HCI research often focuses on front-end interactions, the authors call for a stronger emphasis on sustainable interaction design. The authors posit that user-centred design motivations of individual choice and convenience result in the production of faster and more pervasive, albeit unsustainable and infinitely scalable, growth patterns for digital products and systems known as the 'cornucopian paradigm' (Preist *et al.* 2016). Alternatives to the cornucopian paradigm consider whether the proposed design concept encourages expansion or obsolescence, increase or decrease infrastructural use, the extent of 'digital waste' or avoidance, or shared infrastructures. Casting an eye to the future, Becerik-Gerber *et al.* foreground 10 considerations for the development of HBI research to improve wellbeing (Becerik-Gerber *et al.* 2022). In considering the applications to improving future pandemic preparedness, HBI researchers and designers will need to address contextual particularities. Varied populations with different socio-economic and cultural backgrounds or neurodiverse groups, for example, will require context-specific HBI solutions to enable more inclusive user experience of public places, especially during periods of crisis (Becerik-Gerber *et al.* 2022). The political–economic context also warrants scrutiny as the urban setting or backdrop is closely related to which smart technology governance strategies are implemented to address urban pandemics (Gasser *et al.* 2020; Lee & Lee 2020). Urban populations differ in the respective levels of democratic input and autonomy and this is at odds with universal applications of HBI principles. The further development of these principles will require attention to contextual differences and be informed by a range of stakeholders to produce more sustainable, equitable and trustworthy solutions (Becerik-Gerber *et al.* 2022; Preist *et al.* 2016). Lastly, there is a need to ensure the scalability of HBI solutions across single buildings to multiple buildings and the urban scale by embodying personal, interpersonal, communal and societal interactions (Becerik-Gerber *et al.* 2022). The principles of use, consent and access, and permanence discussed in the preceding sections can serve to inform the development of protocols and practices to enable sharing of data and network resources across increasingly interconnected urban centres.

5. CONCLUSIONS

Surveys of urban history from ancient times to the contemporary era reveal a continuum of public responses to the outbreak of disease such ranging from physical built solutions to specialised digital technologies. These responses continue to reconfigure the relationship between urban residents, the built environment and disease. This paper draws on observations from the COVID-19 era which has featured a complementary suite of pandemic urban responses, encapsulated by three thematic strategies: distancing and separating, monitoring and tracing, and sanitising and cleansing. Table 2 summarises these categories in relation to HBI principles to map the resulting sociospatial implications for urban residents.

Applying HBI principles to the defined responses of distancing and separating, monitoring and tracing, and sanitising and cleansing highlights spatial, ethical and temporal concerns of pandemics for urban residents. An example of an analogue change of use related to pandemics and the built environment arises through repurposing existing buildings for COVID-19 patients, while digital conference software enables online collaboration, in addition to managing local and international patterns of movement through regional and national border regulation, and use of physical and digital signage, protective screens and masks. In contrast, analogue manifestations of 'personal consent and public access' include historical disease maps produced by physicians to visualise and track the spread of pathogens, which have transitioned to biometric wearables and digital surveillance in the current information age. Third, analogue examples of 'permanence' related to pandemics include the construction of new urban sanitation infrastructure, while digital examples include ubiquitous surveillance practices embedded in the built environment on a long-term basis.

These interventions also demonstrate that vulnerability to the physical risks of disease and personal data privacy breaches is not equally spread across urban populations. Nevertheless, myriad applications of digitalisation in urban pandemic management are reflected by close

integration within public health agendas. The HBI framework highlights spatial, ethical and temporal considerations that arise in the ongoing development and application of new digital tools. Future development of HBI concepts should include additional thematic criteria to assess the political–economic factors comprising the context within which urban pandemic responses are developed and implemented. More equitable and inclusive interactional choices for urban residents can be developed through a more nuanced understanding of specific sociospatial environments. Contextualising the sociospatial impacts of pandemic digitalisation contributes to further humanising the sustainable smart city.

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Table 2 Categories of urban pandemic responses in the built environment, related to human–building interaction (HBI) principles.

PANDEMIC RESPONSES	CHANGES IN USE (SPATIAL)	PERSONAL CONSENT AND PUBLIC ACCESS (ETHICAL)	PERMANENCE (TEMPORAL)	STAKEHOLDER IMPLICATIONS AND RESPONSE
Distancing and separating	Intentionally generates physical zones of disease and absence of disease Restricts human movement Reuse of existing buildings and construction of new, dedicated healthcare facilities Temporary installation of physical barriers and signage	Travel restrictions (*e.g.* vaccination passes) and national border controls Public event restrictions in audience attendance and cancellation	Short-, medium- and long-term interventions allowing varying degrees of individual freedom of movement and interaction	*Citizens:* Changes in use of public space, potential loss of civil liberties *Designers and decision-makers:* Understanding changing user needs, designing inclusive public spaces *Researchers:* New theoretical perspectives on public interaction in urban spaces
Monitoring and tracing	Some sustained use of public urban spaces achieved through urban surveillance (*e.g.* automated counters to record user numbers)	Restricted uptake of digital contact tracing in response to personal privacy concerns National governments mandating use of digital platforms and wearables for public health monitoring	Temporary and long-term collection, storage, and transfer of personal data	*Citizens:* Increasing concerns about geo-surveillance, wariness of providing individual data for public health monitoring *Designers and decision-makers:* Managing tensions between public access to urban space and the collection of biometric data *Researchers:* Developing ethical frameworks with respect to the digitalisation of cities
Sanitising and cleansing	Construction and use of new public sanitation infrastructure in urban centres	Unequal public access to urban sanitation infrastructures across the Global North and South	Temporary installations such as hand-sanitiser dispensers complementing the long-term presence of urban sanitation infrastructures	*Citizens:* Increased access to sanitation services, potential for geo-surveillance during periods of crisis and beyond *Designers and decision-makers:* Managing public spaces to protect public health, regulating use of data for surveillance of urban residents *Researchers:* Developing smart technologies to upgrade urban sanitation services

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S.V. undertook theoretical conceptualisation, literature review, analysis and revisions. A.K. and E.E. guided research design, analysis, editing and revision.

COMPETING INTERESTS

The authors have no competing interests to declare.

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