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Research Article

Strengthening Urban Resilience: A Case Study of Amsterdam's Public Spaces in the Post-COVID Era through Digital Solutions

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ABSTRACT

Given the escalating use of digital tools and the Internet of Things in public spaces for quality control, there is an imperative need to address the following question: How can cities enhance the adaptability of their public spaces in the face of various risks and threats, especially those with consequences spanning all urban areas? The COVID-19 pandemic directed unprecedented attention to public spaces, prompting studies on the role of their digitization in influencing their usage during times of crisis. Here, the question arises: Can digital transformations in public spaces be beneficial during crises? While the digitalization of public spaces has its critics, as examinations indicate, the use of certain tools in these locations during the pandemic was able to positively impact their performance. Amsterdam, through the utilization of digital solutions during the COVID period, functioned notably as a significant case study in enhancing the efficiency of public spaces. The aim of this study is to examine the creation of a comprehensive framework that investigates some of Amsterdam's public spaces during the pandemic. The focus of this study is on evaluating the digital solutions applied to public spaces, with an emphasis on resilience against unforeseen challenges. A list of some digital tools that have made public spaces adaptable during the COVID period is reviewed in this section. In essence, the goal is to learn lessons from Amsterdam and present this perspective for similar experiences in cities worldwide to contribute to the resilience and strengthening of their public spaces.

Keywords: Public space, Digitalization, COVID-19 pandemic, Urban Resilience, Amsterdam

Kentsel Dayanıklılığın Güçlendirilmesi: Dijital Çözümler Yoluyla COVID Sonrası Dönemde Amsterdam'ın Kamusal Alanlarına İlişkin Bir Örnek Çalışması

ÖZET

Kalite kontrolü için kamusal alanlarda dijital araçların ve Nesnelerin İnterneti'nin artan kullanımı göz önüne alındığında, şu soruyu ele alma zorunluluğu ortaya çıkıyor: Şehirler, özellikle çeşitli riskler ve tehditler karşısında kamusal alanların uyumlanabilirliğini, özellikle sonuçları tüm kentsel alanları kapsayacak şekilde nasıl arttırabilir? COVID-19 salgını, kamusal alanlara benzeri görülmemiş bir ilgi

çekerek, kriz zamanlarında bu alanların dijitalleştirilmesinin kullanımlarını etkilemedeki rolü üzerine çalışmalara yol açtı. Burada şu soru ortaya çıkıyor: Kriz dönemlerinde kamusal alanlardaki dijital dönüşümler faydalı olabilir mi? Kamusal alanların dijitalleşmesine karşı eleştiriler bulunsun da, incelemelerin gösterdiği gibi, pandemi sırasında bu yerlerde belirli araçların kullanılması performanslarını olumlu yönde etkileyebildi. Amsterdam, COVID döneminde dijital çözümlerden yararlanarak kamusal alanların verimliliğini arttırmada önemli bir örnek alan çalışması işlevi gördü. Bu çalışmanın amacı, pandemi döneminde Amsterdam'ın bazı kamusal alanlarını inceleyen kapsamlı bir çerçevenin oluşturulmasını sağlamaktır. Bu çalışmanın odak noktası, kamusal alanlara uygulanan dijital çözümlerin, öngörülemeyen zorluklara karşı dayanıklılığa vurgu yaparak değerlendirilmesidir. Bu bölümde, COVID döneminde kamusal alanları uyarlanabilir hale getiren bazı dijital araçların listesi incelenmektedir. Temelde amaç, Amsterdam'dan dersler çıkarmak ve dünya çapındaki şehirlerden elde edilen benzer deneyimlerin perspektifini sunarak kamusal alanların dayanıklılığına ve güçlendirilmesine katkıda bulunmaktır.

Anahtar Kelimeler: Kamusal alan, Dijitalleşme, COVID-19 pandemisi, Kentsel Dayanıklılık, Amsterdam

I. INTRODUCTION

A. CONTEXT OF THE COVID-19 PANDEMIC AND ITS IMPACT ON URBAN PUBLIC SPACES

With the start of the COVID-19 pandemic in 2019 and the subsequent enforcement of restrictions in urban areas, the management of public spaces gained increased prominence within governmental control. Transferring in-person interactions from limited physical spaces to digital spaces was one of the solutions that were quickly adopted by the population, as physical encounters were restricted. New solutions to host social activities remotely accelerated the infusion of the digital sphere across society. In this context, urban planners and architects confronted new challenges to approach the cities of the future. Although the degree of digitalization of public spaces was different across developed and developing countries, digital infrastructure played a pivotal role in facilitating pandemic control measures. Despite a substantial portion of social and business encounters moving into virtual platforms, the undeniable importance of physical public spaces persisted during this period. The global response to the COVID-19 pandemic led to a wide range of measures that significantly impacted everyday life, personal freedoms, and the economy. Various scholars concluded that vulnerable groups experienced the most significant impact during the onset of the outbreak [1]. This study focuses on the Netherlands, where measures included curfew, the closure of education centers, social, cultural, and leisure places, and sporting events. Moreover, the size of social gatherings in public spaces and private homes was regulated, and protective masks and social distancing became norms [2]. The COVID pandemic was not the first time in history that public space was affected by major forces. However, the 21st Century pandemic was the first time in which digital tools and applications could be utilized to quickly offer solutions that were adaptable to fast-changing regulations, to public and private spaces, aligned with both local and EU-wide regulatory frameworks, and open to all areas of society (governments, business, and people).

B. THE SHIFT TO DIGITALIZATION AND ITS IMPLICATIONS

The COVID-19 crisis can be seen as a catalyst for the acceleration of digitalization [3], particularly as digital tools became essential for maintaining health and safety. During the pandemic, many individuals were forced to quickly adapt to using digital technologies, driven by the need to learn how to navigate them for work, education, and daily life. This rapid shift helped expedite the learning process for various digital platforms and tools. However, the pandemic also exposed the limitations of

existing infrastructure and government systems in different countries. While physical digital infrastructure in cities is vital, it is not the sole requirement for successful digitalization [4]. Equally important is the need for a clear agenda in education that ensures all segments of society are included and equipped to navigate the digital landscape.

C. IMPORTANCE OF DIGITAL SOLUTIONS IN PUBLIC SPACE MANAGEMENT POST-COVID

Given the innovative nature of digital solutions implemented during the pandemic to manage public spaces, it is now imperative to evaluate their deployment processes and assess their impact on the post-pandemic city. This study aims to describe the digital solutions considered for public space management in Amsterdam during the pandemic. This comprehensive review outlines measures essential for fortifying the resilience of cities in public spaces against similar threats, drawing on the experiences adopted by Amsterdam during COVID-19. The article specifically focuses on cataloging the diverse tools utilized in Amsterdam during this period and scrutinizing their effectiveness in supporting the use of public spaces both during and after the pandemic. The questions guiding this review are:

How can cities leverage digital tools and the Internet of Things (IoT) to enhance the flexibility of their public spaces in response to various hazards and threats, especially those with widespread urban consequences?

How did Amsterdam utilize digital solutions during the COVID-19 period to increase the efficiency of its public spaces?

D. HISTORICAL CONTEXT OF URBAN PANDEMICS AND TECHNOLOGICAL ADVANCES

Cities with high population density provide an ideal setting for the rapid spread of viruses. COVID-19 is not the first pandemic to affect urban areas; historical examples like the Spanish flu, cholera, and the plague have had significant impacts on city populations [5], [6]. The severe consequences of these pandemics have also driven innovations and the development of modern urban planning solutions [7]. The cholera outbreaks of the 19th century, for example, led to significant advancements in urban sanitation and public health infrastructure. Cities like London developed extensive sewage systems and clean water sources in a concerted effort to combat the widespread transmission of the disease [8]. Similarly, the 1918 Spanish flu pandemic highlighted the need for open-air spaces in urban areas. It was observed that a combination of fresh air and sunlight might help reduce the risk of secondary respiratory infections. This led to a greater emphasis on expanding parks and open public spaces to create healthier living environments for city residents [9]. Following the rise of tuberculosis epidemics in the 19th century in North America and Western Europe, cities adopted new strategies for public spaces. These efforts resulted in an increased presence of green areas and the development of housing policies that regulated the layout and design of buildings to ensure that every home had access to natural light [10]. The COVID-19 pandemic also accelerated progress in certain areas of digital infrastructure, particularly within health systems. For instance, in Turkey, telemedicine was promoted through tools such as the 'Hayat Eve Sığar' (Life Fits Home) [11] app and the E-Nabız health system, both of which helped track COVID-19 symptoms, manage hospital capacities, and monitor public health. Additionally, the pandemic spurred the development of public health monitoring systems, including the Crowd Monitoring System Amsterdam (CMSA), which helps manage crowd density in urban areas. Over the last few decades, large technological advances have coevolved with increased urbanization [12], setting the stage for even more rapid changes during the COVID-19 pandemic. The

rise of telemedicine, digital health systems, and public health monitoring technologies reflects this broader trend, as these innovations helped urban centers adapt to new public health challenges.

In this context, the pandemic significantly accelerated the digital transformation of public services, particularly through the shift to online platforms. This transformation not only streamlined service delivery but also enhanced social participation and increased transparency in governance [10].

E. TECHNOLOGICAL TOOLS DURING THE PANDEMIC AND THEIR APPLICATIONS

During the COVID-19 pandemic, the use of digital technologies played a central role in monitoring health and enforcing public safety measures. For example, infrared thermal cameras were used at airports in Taiwan to capture images of individuals with a fever, and in Singapore, temperatures were measured upon entering schools, workplaces, and public transportation [13]. Other technologies, such as surveillance cameras with facial recognition capabilities, drones for services like food delivery and crowd monitoring, and robots for disinfection and medication delivery, became widespread during the pandemic [14], [15].

F. AMSTERDAM'S DIGITAL RESILIENCE AND PUBLIC SPACE MANAGEMENT

The COVID-19 pandemic has underscored the need for cities to adapt and innovate digitally to ensure resilience, particularly in managing public spaces and urban systems. De Lucas Ancillo et al. (2021) argue that the digital transformation resulting from the pandemic is not simply a shift from traditional methods to digital alternatives; rather, it necessitates a fundamental break from previous operational models [16]. This transformation, driven by health crises, accelerates innovation, with cities becoming key sites for testing and implementing new digital solutions. During the pandemic, there was an increased focus on maintaining health and promoting a healthier lifestyle, particularly in urban settings. The importance of urban green spaces and car-free areas (such as more space for walking or cycling) rose significantly. This focus on health was intertwined with the broader digital transformation, as cities leveraged technological tools to create smarter, more resilient spaces. While the pandemic created opportunities for innovation, it also accelerated pre-existing inequalities, as access to digital solutions was not uniform across populations [17]. Amsterdam, alongside cities like London, Paris, Dublin, and Frankfurt, stands out as a key hub in Europe's digital infrastructure, thanks to its high concentration of data centers. These centers are crucial for managing the massive flow of internet traffic across Europe, with much of the data being exported to users outside the country. Amsterdam's role as a critical data exchange hub has only grown, underscoring the city's reliance on a robust digital infrastructure to handle increasing demands, particularly during a global crisis like the pandemic [18].

The pandemic also highlighted how digital technologies can be mobilized to control public health crises. Governments around the world, including the Netherlands, leaned on technological solutions to manage public spaces and reduce transmission. Digital platforms were used for everything from healthcare management to facilitating remote work and virtual interactions. Technology was pivotal in enabling society to cope with lockdown measures and avoid the worst effects of the pandemic [19]. The Netherlands' approach to managing the COVID-19 pandemic, particularly through its "intelligent lockdown" policy, differed from that of many other European countries. While countries like Italy and France implemented strict national lockdowns and restricted non-essential travel, the Netherlands adopted a more flexible strategy, balancing public health concerns, economic impact, and protection of vulnerable individuals. This policy included measures such as the closure of cafes, schools, and gyms, but allowed people to move freely while observing a 1.5-meter social distancing rule. A study by Haas, Faber, and Hamersma (2020) [20] found that 80% of people reduced their outdoor activities,

with elderly individuals being particularly affected. Furthermore, 44% of workers began working from home, and 30% shifted to holding more meetings online. While the "intelligent lockdown" was a nationwide strategy, other cities in the Netherlands, such as Rotterdam and Utrecht, adopted similar measures. Digital tools for crowd monitoring, social distancing enforcement, and sensor-based technologies were widely used across the country to mitigate the spread of the virus and ensure public safety in crowded spaces [17].

At the beginning of the pandemic, the Netherlands, like countries such as Germany, France, and Italy, implemented similar strategies for social distancing, wearing masks, working from home, and protecting healthcare infrastructure. However, the Netherlands' "intelligent lockdown" strategy differed from other countries because it primarily emphasized personal responsibility and individual behavior. Unlike its neighboring countries, which adopted stricter measures, the Dutch government focused on personal responsibility, keeping schools open, and relying on individuals to follow social distancing guidelines. The aim of these policies was to prevent overwhelming the healthcare system and minimize economic disruptions. Significant financial support was also provided to businesses, which helped mitigate the negative economic effects. Overall, the Netherlands positioned itself between Sweden's more lenient approach and Germany's stricter policies, achieving relatively favorable health and economic outcomes, although it faced challenges [21].

In particular, as the largest city and capital of the Netherlands, Amsterdam attracted more attention during the COVID-19 pandemic due to its dense population and large number of tourists. The city adopted digital solutions to control and prevent further spread of the virus, thanks to its stronger digital infrastructure and data-driven approaches compared to other cities. Public spaces and public transportation systems received significant attention during this period. Due to Amsterdam's differences from other cities in terms of innovative technologies, it was chosen as a case study.

G. TURKEY'S DIGITAL ADAPTATION IN PUBLIC SPACE MANAGEMENT DURING THE COVID-19 PANDEMIC

While Amsterdam's rapid adoption of digital solutions during the COVID-19 pandemic showcases a model of innovation within Europe, Turkey's digital transformation offers a broader perspective on how different regions implemented technology to address the pandemic's challenges. Both cities embraced digital tools, but their strategies were shaped by distinct socio-political contexts and infrastructural needs. Amsterdam focused on remote work and online services, while Turkey expanded its digital services in healthcare, government, and local municipalities, providing a more holistic national digital response. For example, Turkey significantly expanded its e-government services, increasing the number of available services from 5,058 in 2020 to 6,664 by 2022 [22]. This expansion made it easier for citizens to access essential services such as social support applications, travel permits, and address changes. In parallel with Amsterdam's digital push for remote work platforms, Turkey also emphasized telemedicine, using tools like the "Hayat Eve Sığar" (Life Fits Home) [11] app and the E-Nabız health system to track COVID-19 symptoms, manage hospital capacities, and provide remote health consultations [22]. These systems not only allowed citizens to schedule vaccinations but also facilitated access to critical health data, reducing the need for in-person healthcare visits and supporting those with limited access to medical facilities [23]. Additionally, Turkey's national and local governments played a crucial role in accelerating digital transformation. Municipalities like Bartın, Beşiktaş, and Trabzon transitioned many services to digital platforms, including virtual cultural events and smart systems to enforce social distancing and mask-wearing. These local initiatives helped address the immediate needs of urban populations during lockdowns and mobility restrictions [24], [25]. While Amsterdam also advanced its digital infrastructure to facilitate city services, Turkey's focus on local government digitalization, alongside national healthcare efforts,

illustrates a comprehensive approach to digital governance. Both countries faced challenges in addressing the digital divide, but Turkey's experience underscores the importance of improving digital literacy and ensuring equitable access to technology for all citizens [4].

H. METHODOLOGY

This study builds upon the work of Hueck [26], whose research examined the ways young adults in Amsterdam attributed significance to public spaces during the COVID-19 pandemic, focusing on their increased appreciation, participation, and emotional connection to these spaces. In particular, Hueck's study found that during the lockdown, public spaces served as vital locations for social interaction, identity formation, and well-being. In contrast, this research specifically investigates the role of digital tools and technologies that were implemented in Amsterdam's public spaces during the same period to enhance their functionality and resilience. These tools were part of the city's broader effort to adapt urban environments in response to the pandemic and ensure public safety while facilitating the continued use of public spaces.

The methodology employed in this study involves two main data collection approaches:

Field Observations: The researchers conducted direct observations in various public spaces across Amsterdam, such as Vondelpark, Marineterrein, and Kalverstraat, to examine the integration of digital tools, including smart cameras, decision-support systems, sensors, and AI applications. The focus was on how these technologies were used to manage crowd density, facilitate social distancing, and monitor public health compliance. Observational data was collected on the types of digital tools deployed, their visibility and accessibility to the public, and how they contributed to reshaping public space use during the pandemic.

Document and Report Analysis: The study also utilized secondary data from official reports, government publications, and urban planning documents published during and after the pandemic. These sources include technical descriptions of the digital tools implemented in public spaces, such as the Privacy-by-Design Public Eye system, Crowd Management Decision-Support Systems (CM-DSS), smartphone applications, sensors, and AI-driven solutions like the Fitness Garden at Marineterrein. The analysis of these documents provided insights into the rationale behind the deployment of these technologies, their functionality, and their role in ensuring public health safety.

This mixed-methods approach—combining real-world observations with an in-depth review of official data—allowed for a comprehensive analysis of how digital tools were utilized in Amsterdam's public spaces. By focusing on how these technologies were integrated into urban environments, this study aims to assess their effectiveness in promoting public safety, enhancing public space resilience, and supporting the reconfiguration of public spaces during a global health crisis.

II. THE ROLE OF PUBLIC SPACE DURING THE TIME

Ali Madanipour's definition of public space is articulated as "a space that allows all people to have access to it and the activities within it, which is controlled by a public agency and provided and managed in the public interest" [27]. This conceptualization establishes a foundational understanding wherein public spaces are construed as entities overseen by public authorities for the collective benefit. Throughout history, public spaces held major significance for both citizens and governing bodies, serving such diverse functions as social participation, political protests, declarations of solidarity, and hosting cultural interactions. The dynamic nature and continual evolution of public space can be observed despite experiencing morphological and functional shifts across historical periods, public spaces persist as pivotal urban elements. The evolution of public spaces has been significantly shaped

by successive historical periods, such as industrial revolutions, transportation trends, and popularization of specific urban fabric types. The contemporary digital revolution has introduced electronic devices, digital equipment, smart technologies, and the Internet of Things, reinforcing the trend of “privatization” within public spaces. This nuanced historical examination, complemented by Madanipour's elucidation, enhances scholarly comprehension of s within urban landscapes.

The urban setting presents a range of physicochemical dangers, encompassing pollution, traffic-related risks, and the exacerbation of heat waves attributable to the "urban heat island" effect. Furthermore, limited space for walking, cycling, and active lifestyles contributes to cities becoming hotspots for the non-communicable diseases epidemic and catalysts for climate change [28], [29]. This complex scenario can be ascribed to multiple factors, including pollution, inadequate sanitation, rising stress levels, dietary habits, and insufficient physical exercise.

Similarly, cities in the 19th and early 20th centuries were afflicted by infectious diseases that thrived in crowded conditions. Inadequate sanitation and dismal living conditions contributed to devastating outbreaks of influenza, typhus, and tuberculosis, claiming the lives of millions of people [30]. Given the emphasis on the significance of public spaces, it becomes imperative to urgently address the need to enhance the resilience of cities. Now, the question arises as to what strategic measures are necessary to implement this goal.

III. THE IMPORTANCE OF URBAN RESILIENCE

Resilience refers to a system's ability to endure disruptions, adapt to changes, and restructure itself while maintaining its fundamental function, structure, identity, and feedback mechanisms [31]. This resilience operates at various levels, encompassing the individual, community, systems, and institutional domains, facilitating interaction with hazards or stressors while enhancing cooperation between entities to maintain or restore function. The ultimate goal is to adapt to a new balance while minimizing the accumulation of previous or additional risks and vulnerabilities [32].

Urban resilience, within this framework, entails creating approaches to enhance the management of urban areas, ensuring their functionality in the face of destructive incidents. Urban resilience is defined as the ability of an urban system – and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales – to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity [33].

The significance of healthy urban environments and access to quality public spaces and natural areas, which have been underscored [34], [35], has become more pronounced in the aftermath of the pandemic. It has highlighted the central role of these spaces in enhancing physical and mental well-being [36], [37]. Research has indicated that elements related to the quality of air [38], [17], the handling of waste [40], [41], public transportation systems [42], [43], sanitation infrastructure [44], [45], and public spaces [46], [47] may impact the transmission of viruses [48]. As urban areas undergo adjustments and recovery, it is crucial to prioritize the creation and upkeep of public spaces that are accessible and inclusive [48]. This is vital for fostering healthier and more resilient urban communities. Insufficient access to parks and recreational areas exacerbates these difficulties, restricting chances for physical activity and meaningful connection with nature, both of which are essential for mental well-being [49], [50]. In general, increasing resilience in public spaces by increasing people's access to these spaces for physical activities, engagement with nature, communication in open spaces can increase the well-being of residents and lead to social cohesion.

While leveraging smart tools and information technologies can enhance the efficiency of urban systems and align them with evidence-based paradigms during crises, it is imperative to acknowledge that resilient urban planning should facilitate fair access to resources and address structural inequalities and vulnerabilities in societies [51], [52]. This consideration is essential to prevent the exacerbation of social crises within this context.

A.THE IMPORTANCE OF PUBLIC SPACE IN BUILDING URBAN RESILIENCE DURING THE PANDEMIC

In the past, the implications of health crises have been instrumental in influencing the trajectory of urban planning and design. Significant measures were undertaken to ameliorate living conditions within cities, including the implementation of robust sanitation and hygiene practices, the introduction of expansive boulevard streets, and the establishment of zoning regulations aimed at delineating industrial activities from residential areas. It is widely recognized that the built environment has a significant impact on both physical and mental health [53], [54].

The COVID-19 pandemic also led modifications in the urban environment with a major difference: instead of morphological changes, measures were mostly regulatory. During the first waves, open public spaces, including streets, urban squares, sidewalks, open markets, some recreational areas, as well as closed public spaces like shopping centers, public libraries, bars, cafes, and certain public buildings, came under the control of government agencies and faced restrictions, limiting presence and sometimes leading to strict control measures and nudging social practices to shift into the virtual realm [55]. Location data, mobile phone apps, digital cameras, and other digital methods were extensively utilized in the public domain, receiving strong support from governments and relevant stakeholders in their fight against the virus. According to Jacobs (1993) [56], urban vitality is usually associated with perception of security, and vice-versa. Paradoxically, the situation seemed to be reversed during a pandemic, when an empty street became a secure location in terms of minimizing the risk of virus transmission [57].

After the first waves of the virus the re-opening phase started. Governments put emphasis in gradually regaining social life while maintaining control over these spaces with measures such as biometric mass surveillance, temperature checks, and the increased deployment of digital tools in public areas, including surveillance cameras, were employed to prevent the spread of the disease.

It is arguable that public spaces accelerated an already ongoing process of digitalization using the pandemic as a catalyst for testing and implementing solutions [58], [59], especially in the fields of surveillance, facial recognition, and location tracking, but also in general smart city development, telemedicine, online commerce, and education, and multiple other fields of ICT.

B. URBAN RESILIENCE THROUGH DIGITAL SOLUTIONS IN PUBLIC SPACES

The main advanced technologies used for overseeing public spaces include biometrics, closed-circuit television (CCTV), smart identification cards, and electronic devices that monitor and track information communication [60]. Sophisticated technologies and devices, originally designed for securing highly guarded facilities, are increasingly being utilized for monitoring public spaces, surveilling city streets and squares, and enabling the identification of car registration numbers and permits (e.g. LEZ stickers). When coupled with biometric databases, they also allow for facial recognition even when wearing masks. In the context of the COVID pandemic, biometric readers combined with temperature sensors could identify infected individuals in crowds, while mobile phones were used to trace back the movements of specific individuals and reconstruct their personal and social networks. In this context, real-time monitoring and analysis of big data play a crucial role in effectively responding to disruptive events. The combination of IoT sensors, smart city systems, and machine learning techniques can yield significant achievements. The pandemic presented an unparalleled opportunity to gain insights into the impact of global emergencies on cities and take actions to minimize their effects, thereby enhancing urban pandemic resilience [61].

Since the 1990s, there has been a resurgence in interest regarding the connection between health and urban planning, elevating it to a specialized area of study. In the past years, this trend has been aligned with the rapid digitization of urban spaces as a result of the COVID crisis. Hence, it is evident that digital technologies hold the capacity to act as a transformative influence in shaping the future of cities and public spaces by being rapidly adaptable to respond to specific needs or crisis [62] and therefore become one of the key enablers of urban resilience. After the COVID pandemic, the discussion on threats and challenges that cities are facing shifted from urban health to climate and energy crisis. Once again, advanced technologies implemented in public space monitoring and city management and decision-making assessment are emerging as a fast and easy-to-deploy solutions targeting the causes and effects of urban threats and challenges. Technological developments to monitor and control

energy consumption of buildings, traffic congestion, or vehicle access to areas might have the same underlying concepts as those implemented for people-tracking during the pandemic, funneling urban resources to mitigate negative impact of stressors, therefore making cities resilient entities.

IV. CASE STUDY: AMSTERDAM'S RESPONSE TO COVID-19

Urban resilience has always been one of the main focuses in Europe in the face of shocks and challenges such as natural disasters, epidemics and crises. The European Union (EU) expressed its inclination towards the advancement of secure and inclusive technology, offering a valuable foundation for the creation of digital public spaces and offering an alternative perspective on technology, emphasizing collective public values instead of market or state values [63]. In this context, Amsterdam's substantial investments in digital infrastructure endowed it with the capacity to effectively monitor and oversee public spaces. Amsterdam adeptly alleviated the challenges posed by the COVID-19 pandemic through the utilization of its well-established smart infrastructure. Moreover, the implementation of digital solutions fostered a cohesive environment between citizens and governance, facilitating enhanced decision-making processes, facilitating valuable feedback mechanisms, and facilitate people's reentry into public spaces and enhance their utilization during the pandemic period.

This research builds upon Hueck's study (2021), who examines the way young adults attributed importance to public spaces in Amsterdam during the COVID-19 pandemic by evaluating their appreciation, participation, and emotional connection. During the lockdown in Amsterdam, respondents regarded public spaces as locations that: (i) garnered increased appreciation, (ii) contributed to the development of youth identity, and (iii) played a vital role in well-being [26].

In this study, we investigate digital tools and solutions which utilized in Amsterdam public spaces to enhance their function during the COVID-19 period. The main objective of this study is to examine the tools and approaches that have assisted government and municipality of Amsterdam in the reutilization of public spaces during this period. The methodology employed in this research encompasses data collection through observation and gathering information from published reports during that period.

A. ENHANCING URBAN RESILIENCE: IMPLEMENTATION OF DIGITAL TOOLS AND TECHNOLOGIES IN AMSTERDAM'S PUBLIC SPACES

Amsterdam emerged as a beacon of urban resilience through the strategic implementation of digital tools and technologies in its public spaces, particularly during the challenging times of the COVID-19 pandemic. The city's innovative approach encompassed a comprehensive array of solutions, including Smart Cameras, Decision-Support Systems, Applications, Sensors, AI Applications, and Digital Mapping Tools. Amsterdam's multifaceted approach to incorporating digital tools and technologies in public spaces reflected a forward-thinking and adaptable urban strategy. While navigating the complexities of the pandemic, the city set a benchmark for leveraging innovation responsibly, ensuring public safety, and fostering a resilient urban environment.

A. Smart Cameras

In managing public spaces during the COVID-19 era, Amsterdam utilized city surveillance systems, famously known as the 'Public Eye,' to ensure public safety and compliance with health regulations. Innovative digital tools played a significant role in facilitating social distancing measures in crowded areas.

Amsterdam pioneered the use of population monitoring technology with its Privacy-by-Design Public Eye system. The Public Eye system for head-counting employs pre-existing city cameras along with a novel artificial intelligence (AI) algorithm based on computer vision technology. This combination is utilized for the monitoring and prediction of crowd size, density, direction, and speed within public spaces, and it was further customized to gauge compliance with social distancing measures during the pandemic [64].

The features of advanced surveillance systems, utilized for monitoring public spaces during the COVID-19 pandemic in Amsterdam, are detailed in Figure 1.

Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area
Smart Cameras		3D Crowd sensors and cameras for emergency regulation Corona. Source: Responsible Sensing Lab - CMSA Project Report, 2020
	1- Detecting count of people by head (no facial recognitions)	Marineterrein Test Zone for innovation and its map at the entrance. Source: May 2022. Hülya Lasch.
	2- Accelerated deployment and integration with video analytics	Marrineterrein Shutter camera, camera sticker and the information board. Source: May 2022. Hülya Lasch.
	3- People counting for restricted entrances	
	4- Counting people for crowd management due to corona regulations (Public Eye)	Fitness Garden at Marineterrein. Source: May 2022. Hülya Lasch.
	5- Detecting crowd and social distance violations (>1,5 meter) (Fitness Garden, Marineterrein)	Dam Square Public Eye camera. Source: May 2022. Hülya Lasch.
		Kalverstraat/Muntplein Camera and camera sticker. Source: May 2022. Hülya Lasch.

Figure 1. Digital tools used in public space, smart cameras, Source: Authors

B. DECISION-SUPPORT SYSTEMS

Amsterdam implemented digital tools employing sensors, cameras, and AI to monitor and enhance crowd management during the COVID-19 pandemic. While these technologies played a crucial role in mitigating the virus's spread and ensuring public safety, they also raised concerns about increased surveillance, privacy infringement, and data security. The City of Amsterdam is developing a Crowd Management Decision-Support System (CM-DSS) as part of the CityFlows project, funded by the European Institute of Innovation and Technology (EIT) Urban Mobility initiative, to actively monitor and manage crowded spaces using real-time decision support systems. Originally intended for large events, the project has adapted to the new reality by implementing crowd management systems to monitor social distancing at busy locations. The system produces real-time data, aiding city officials in informing social-distancing measures through dashboards [65], [66].




Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area	
Technical tools	1- Crowd monitoring physical information dashboards - Crowd	Marrineterrein Dashboard. Source: May 2022. Hülya Lasch.	
	Management Decision-Support (CM-DSS) System (Marrineterrein)	Dam Square camera sticker with a unique ID-Code. Source: May 2022. Hülya Lasch.	
	2- Cameras and camera stickers (Crowd Management Decision-Support (CM-DSS) System)	Dam Square camera sign. May 2022. Hülya Lasch.	

Figure 2. Digital tools used in public space, Decision-support systems, Source: Authors

C.APPLICATIONS

During the COVID-19 pandemic, Amsterdam implemented various smartphone applications to address crowd monitoring and control, as well as proximity tracing. Citizens were informed about the presence and usage of crowd monitoring cameras in public spaces, ensuring transparency in surveillance measures. Additionally, Marineterrein Amsterdam served as a test area for crowd monitoring, offering valuable insights into crowd control strategies and proximity tracing. Public Eye, a prominent tool utilized during this period, provided measurements and data in Vondelpark and contributed to the overall COVID-19 Living Lab project. The Marineterrein DrukMeter, used for monitoring curfew behavior, played a vital role in gathering data during the lockdown. These efforts exemplify the city's commitment to leveraging digital tools and open-source technologies to manage public spaces effectively while ensuring public safety and health during the pandemic.





Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area
Applications	1- information to citizens about crowd monitoring cameras 2- crowd control, proximity tracing	Marineterrein Amsterdam test area for the crowd monitor (Source: Tapp - Smart City Architecture, 2022) 
		Measurements of a day Vondelpark data by Public Eye (Source: CityFlows Project. (n.d.). COVID-19 Living Lab.2022) 
		Corona curfew behavior measurements of Marineterrein DrukMeter during the lockdown (Source: amsterdamsmartcity.com, Tapp 2021) 
		Application of Public Eye for the open-source crowd monitoring at the Marineterrein (Source: Tapp 2021) 

Figure 3. Digital tools used in public space, Applications, Source: Authors

D.SENSORS

Amsterdam has embraced innovative sensor technologies to navigate the challenges posed by COVID-19. The COVID-19 living lab acts as a testing ground for various sensors deployed at prominent locations, including Vondelpark, Albert Cuyp Street, Kalverstraat shopping district, and Marineterrein. These sensors encompass a range of technologies, such as 3D sensors, 2D sensors, NUMINA sensors, RFID sensors, and Public Eye cameras [65]. Real-time data is processed by a 24/7 operational crowd monitoring system and assists in ensuring public safety and compliance with COVID-19 regulations. The Responsible Sensing Lab, in collaboration with the City of Amsterdam, has played a key role in ensuring responsible data collection and public acceptance. They've introduced the Responsible Sensing Toolkit to guide organizations and municipalities in the responsible implementation of public sensors [64] (Figure, 4).

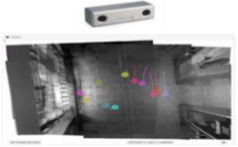
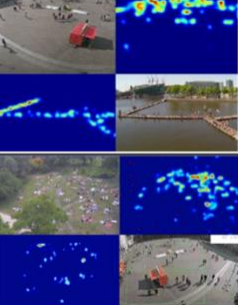
Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area	
Sensors	1. Crowd Monitoring System Amsterdam (CMSA), Count, speed, density, trajectory information and heat maps in terms of Corona emergency regulations 2. Social Distancing Compliance	3D Crowd sensors and cameras for emergency regulation Corona. (Source: Responsible Sensing Lab - CMSA Project Report, 2020)	
		Density map animation (Source: Responsible Sensing Lab - CMSA Project Report, 2020 and Tapp, 2021)	

Figure 4. Digital tools used in public space, Sensors, Source: Authors

E.AI APPLICATIONS

In response to the challenges posed by the COVID-19 pandemic, Amsterdam has leveraged AI applications to enhance public health and wellness initiatives. The city recognized the importance of providing safe outdoor fitness facilities for its residents during lockdowns. As a result, in collaboration with the Marineterrein living lab, Amsterdam introduced the Fitness Garden at Marineterrein, incorporating AI and computer vision technology. This innovative solution employs AI to count the number of individuals using the Fitness Garden while also detecting instances of people coming within a 1.5-meter proximity, adhering to social distancing guidelines. Additionally, IoT technology, coupled with LED lighting, plays a crucial role by dynamically changing the colors of lights based on safe distancing and capacity limits. When the AI identifies people within 1.5 meters of each other, the LED strip turns red, serving as a visual reminder for visitors to maintain a safe distance from one another [64]. This pioneering use of AI technology demonstrates Amsterdam's commitment to enhancing public health and safety during the pandemic.

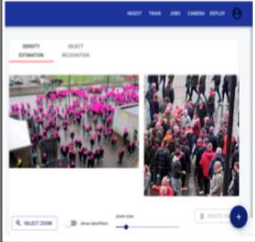



Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area
AI Applications		<p>Open Source AI / Computer vision technology, IoT technology and the LED lighting for detecting social distance violations (>1,5 meter) - the operation of the pressure gauge (Source: https://www.tapp.nl/project-overview/public-eye)</p> 
	1- Detecting count of people by head (no facial recognitions)	<p>Marineterrein Swimming area measurements (Source: https://www.marineterrein.nl/nu/)</p> 
	2- The processing of data collected on digital platforms and mobile networks to track people's recent movements	
	3- Detecting crowd and social distance violations (>1,5 meter) (Fitness Garden, Marineterrein)	<p>The live pressure gauge (Source: https://www.marineterrein.nl/nu/)</p> 
		<p>Amsterdam's Fitness Garden at Marineterrein uses AI and computer vision for crowd monitoring, with AI-driven LED lights promoting safe distancing 24/7. (Source: https://www.tapp.nl/project-overview/ffg)</p> 

Figure 5. Digital tools used in public space, AI applications, Source: Authors

F. DIGITAL MAPPING TOOLS

Amsterdam has implemented digital mapping tools to tackle the challenges of enforcing social distancing during the COVID-19 pandemic. These tools include a mapping application that assesses the feasibility of social distancing in public spaces, with a specific focus on sidewalks and public transportation infrastructure. Additionally, the Social Distancing Dashboard, developed in collaboration with Delft University of Technology and the Amsterdam Institute for Advanced Metropolitan Solutions, offers valuable data to policymakers and city planners, aiding in their decision-making process for COVID-19 interventions [67]. The Municipality of Amsterdam has also introduced the SecDev Urban Pandemic Preparedness Index, a social vulnerability index that visually represents various data across time and space. This tool assists in the efficient allocation of resources during crises, allowing decision-makers to anticipate areas at a higher risk and optimize various aspects of pandemic response, including vaccination distribution, green recovery initiatives, pollution monitoring, and accessible healthcare facilities [68] (Figure, 6).

Digital Tools Used In Public Spaces During The COVID-19 In Amsterdam	Function	Deployment area
Digital Mapping Tools	1- Mapping Crowd Monitoring Sensors and Cameras to inform citizens about personal data processing in the public space	Map of Crowd Monitoring Sensors and Cameras in Amsterdam - Crowd Monitoring System Amsterdam (CMSA) (Source: https://maps.amsterdam.nl/cmsa/?LANG=nl)
	2- Sensors register	Crowd Monitoring Sensor register - Crowd Monitoring System Amsterdam (CMSA) (Source: https://sensorengister.amsterdam.nl/)
	3- The Social Distancing Dashboard Amsterdam	The Social Distancing Dashboard Amsterdam - The SocialGlass research program - The Delft University of Technology and the Amsterdam Institute for Advanced Metropolitan Solutions (Source: https://covid19.social-glass.tudelft.nl/amsterdam/#15/52.3702/4.8952)
	4- Measuring social and urban pandemic preparedness (Index) for disease control and to inform citizens about areas with risk of more infection in terms of vulnerability	SecDev Urban Pandemic Preparedness Index (Source: https://urbanresilience.secdev.com/amsterdam/map)

Figure 6. Digital tools used in public space, Digital Mapping Tools, Source: Authors

V. CONCLUSION

During the COVID-19 pandemic, various measures undertaken by governments and municipalities through digital technologies aimed at facilitating a return to normal urban life and enhancing security and order in public spaces [32]. As we transitioned beyond the pandemic, it became clear that the digital layer played a crucial role in enhancing the resilience of public spaces during other crises. Digital tools offer diverse functionalities that can help cities manage critical situations and adapt to unforeseen challenges. In this context, Amsterdam's successful integration of digital tools for controlling and reclaiming public spaces positioned these technologies as valuable assets within the decision-making processes of local and regional governments. The COVID-19 pandemic accelerated the digital transformation of public spaces, particularly in cities like Amsterdam. The city successfully leveraged a variety of digital innovations—such as smart cameras, technical tools, applications, sensors, and AI applications—to manage and enhance public spaces. These technologies played an essential role in ensuring public safety, monitoring compliance with health regulations, and enabling the safe reutilization of public spaces. The pandemic highlighted the importance of these tools in adapting to the “new normal” and managing the complexities of public space usage during global health crises. Amsterdam's experience serves as a compelling case study for other cities, demonstrating how digital technologies can fortify the resilience of public spaces in times of crisis. However, it is essential to balance the benefits of these technologies with potential concerns related to surveillance, privacy, and data security. Ongoing discussions about the ethical implications of digital tools, alongside the development of governance frameworks that protect privacy, promote

transparency, and maintain public trust, will be critical to ensuring that these technologies are used in ways that are both beneficial and equitable for all citizens. The evolution of public spaces during the COVID-19 pandemic exemplifies the transformative potential of digital technologies in urban planning. As cities like Amsterdam have shown, these tools can play a pivotal role in crisis management, helping urban areas adapt to unforeseen challenges while maintaining public health and safety. However, the future of urban resilience depends not only on technological advancements but also on ensuring these innovations serve the collective good, creating cities that are inclusive, equitable, and prepared for the complexities of an unpredictable future. The lessons learned from Amsterdam's experience, particularly regarding the responsible implementation of digital technologies, can guide other cities in developing strategies that enhance the resilience of public spaces while safeguarding the values of privacy, equity, and community well-being.

In conclusion, the importance of public spaces as sites for social engagement and identity during times of crisis has been underscored by research, such as that by Hueck (2021) [26], which explored how young adults in Amsterdam attributed increased value to public spaces during the pandemic. These spaces were not only essential for maintaining physical distancing but also played a key role in fostering identity, social cohesion, and mental well-being. Amsterdam's response to the pandemic reflected a broader societal understanding of the role public spaces play in building both community resilience and individual well-being. Therefore, cities must prioritize public spaces as integral to urban health and resilience, ensuring that technological advancements align with the collective good and the protection of individual rights. Amsterdam's experience offers valuable insights that can be adapted globally, even in cities with less advanced digital infrastructures. Future research should further explore the long-term impacts of digital tools on quality of life, social interactions, and mental health, as well as comparative studies on the role of digital technology in managing public spaces during crises.

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