Research Paper

Breathing Cities: From Vernacular Production to the Digitalization of Urban Space

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Abstract

Contemporary cities encounter significant environmental, social and technological challenges, including climate change, population growth, and increasing inequalities. This paper examines the environmental challenges while pointing to the limits of traditional planning and design in responding to these shifts. To better understand how cities are changing, the study traces the evolution of sustainability thinking, from vernacular design practices to today's digital and data-driven innovations. The research uses qualitative comparative case study approach. Cities were chosen based on their varied climates, cultural contexts, and sustainability strategies, ranging from low-tech vernacular systems and advanced digital urban models. The study looks at cities such as Singapore, Copenhagen, Masdar City, and The Line, as well as historical examples from Yemen and Morocco, to analyse climate-responsive design, spatial porosity, and material resilience. This paper introduces the concept of "breathing cities", an interdisciplinary framework that reimagines urban sustainability through the convergence of vernacular urban knowledge and digital spatial technologies. The framework positions cities as adaptive, porous, ecologically attuned, and health-cantered systems. Instead of relying on static, technocratic models, the "breathing cities" approach offers a more dynamic way of imagining sustainable urbanism, one that brings together material, spatial, technological, and ecological dimensions. Drawing on theoretical perspectives such as spatial production and post-anthropocentric urbanism, the study calls for a paradigm shift: from cities as objects of control to cities as responsive, co-evolving ecosystems. Ultimately, this paper contributes to a new urban sustainability discourse that reconnects environmental stewardship, social justice, and technological innovation. It proposes a scalable, context-sensitive approach to rethinking how cities can adapt to the challenges of the 21st century, not by abandoning tradition or over-relying on technology, but by bringing them together into an integrated, living urban fabric.

Keywords

Sustainability, Environmental (in)justice, Urban health, Resilience, Vernacular Urbanism, Digital Urban Technologies.

1. Introduction

Cities today are facing multiple environmental, social, and technological pressures. Rapid urbanization, population growth, and accelerating climate change have intensified ecological vulnerabilities, exposing urban populations to rising temperatures, deteriorating air quality, resource scarcity, and widening spatial inequities (Brzosko-Sermak and Winiarczyk-Raźniak, 2025). The Industrial Revolution established urbanization as a development process which transformed both natural environments and geographical boundaries while generating major effects on health outcomes and environmental protection and resource management (Priya et al.,2024). The findings are consistent with industrial cities which have actively removed natural systems that resulted in environmental deterioration and health problems throughout their urban areas (Santamouris, 2019). Consequently, health as a function of the individual's environment and living conditions became a central focus of medical attention as early as the nineteenth century (Davies and Kelly, 1993; Crume, 2019).

The environmental consequences of these transformations, including urban heat islands, unequal exposure to pollution, and differential vulnerability to climate risks, have positioned urban sustainability as a central concern in contemporary urban discourse (Das et al., 2024). Yet, despite decades of policy frameworks and urban interventions, many cities continue to struggle with fragmented planning systems, technocratic approaches, and narrow definitions of efficiency that fail to address the complexity of urban life. Traditional models often treat cities as static, engineered objects, overlooking the dynamic, interdependent relationships that define urban ecosystems (Mora et al., 2023).

The rapid advancement of digital technologies has reshaped urban design (Ash, Kitchin and Leszczynski, 2018). Environmental sensing, data-driven governance, digital twins, and predictive modelling have transformed how cities are monitored, understood, and planned (Sacoto-Cabrera et al., 2025). While these tools offer opportunities for improving sustainability, they also risk reinforcing top-down practices if not grounded in local context, culture, and ecological awareness. In contrast, vernacular urbanism, rooted in centuries of climate-responsive design, material intelligence, and community-based spatial practices, offers valuable insights into how cities have historically adapted to their environments. However, these strategies are often marginalized or romanticized rather than systematically integrated into contemporary planning.

Building on this narrative, the multifaceted nature of urban sustainability remains a both challenging and contested concept (Keivani, 2009). Owens (1992) claims that sustainable urban development is inherently contradictory, explaining that urban areas require the resources of a wider environment for their survival (Owens, 1992). In contrast, others claim that the city itself, as a spatial entity, is an embodiment of sustainability (Breheny, 1992). What is clear, however, is that cities function as essential areas which generate environmental degradation yet they provide opportunities to achieve sustainability.

This study investigates methods to combine digital systems with traditional knowledge for creating urban systems which adapt and maintain their resilience. It investigates how uniting conventional climate adaptation methods with contemporary digital systems will enable the achievement of sustainability goals which meet present-day urban conditions for environmental protection, social needs and technological requirements. This raises critical questions: How can cities continue to grow while sustaining ecological balance? Is the pursuit of urban sustainability a Sisyphean task, or can design truly reconcile ecology and urban life? To answer these questions, the objectives of this study are fourfold: to examine how vernacular strategies inform contemporary digital design; to evaluate the potential of digital technologies in enhancing

sustainability and urban resilience; to propose a comprehensive “breathing cities” framework for adaptive urban ecosystems; and to demonstrate scalable, context-sensitive urban solutions through comparative case studies.

The paper starts by defining urban flux through its relation to contemporary debates on sustainability and environmental (in)justice, and the limitations of traditional planning. The following section examines vernacular urbanism by studying historical examples which show how pre-modern urban systems used climate-responsive design and ecological intelligence in their development. Subsequently, the research examines digital technology through a critical analysis of environmental sensing and digital twins and AI-based governance systems which evaluates their advantages and limitations in present-day smart city systems. The Section 3 presents the "breathing cities" framework which describes its design principles through three core elements which include porosity, adaptability and health-oriented design approaches. The methodological framework appears in Section 4 before the research evaluates global case studies through a comparative analysis of Singapore, Copenhagen, Masdar City, The Line, and selected vernacular precedents, to find common approaches and varying environmental conditions. The discussion examines the upcoming effects of treating cities as co-evolving ecosystems, before it presents the main points of breathing cities which enhance urban sustainability.

2. Lessons from the Past: Urban Transformations and Sustainability

Cities today are an inheritance of the past, an overlay of centuries of civilization. Urban ecosystems are always in flux, with interactions that shift and evolve over time. The growing concern about environmental crises has elicited a variety of responses and models from designers, leading to differing views on ecologically responsive design. As stated by Yeang (1995), design in relation to the earth’s ecological problems must look toward the future and operate in both practical and hypothetical dimensions. These ongoing debates around sustainability and the many ways it is understood continue to influence how we think about cities and their future. Looking back at how cities have changed over time offers important lessons for sustainability today. Vernacular urban practices offered highly adaptive solutions grounded in deep ecological understanding, community needs, and resource efficiency. Oliver (2003) notes that vernacular urbanism, with its focus on flexibility, resourcefulness, and adapting to local contexts, can offer valuable lessons for contemporary urban design. Vernacular cities such as Shibam, Sana’a, Marrakech, and Fez demonstrate climate-responsive design through compact urban forms, shaded narrow streets, earth-based materials, and passive cooling strategies (Fathy, 1986; Bianca, 2000). Different parts of the world demonstrate similar design principles which include Isfahan's courtyard houses, Yazd's wind-catchers, Cairo's mashrabiya screens, and the stilted kampung settlements of Southeast Asia, that reflect how people have adapted to their environment through time (Rapoport, 1969; AlSayyad and Massoumi, 2011). The local knowledge systems developed distinct environments which proved their resistance to outside change through their cultural and environmental ties.

Today, cities work to re-establish their connection with traditional design elements which people used to consider as common practice. Yet solutions often consist of selecting the most “obvious” or easily implemented interventions, which tend to be reactive rather than systemic. The renewed interest in vernacular thinking is very often reduced to surface-level borrowing, such as adding shading elements or green façades, without understanding the fundamental social and environmental principles which created sustainable urban designs in the past.

Contemporary urban planning and design are increasingly characterized by the integration of computational technologies, which facilitate the management and analysis of vast datasets. Digital tools enable planning professionals to perform essential tasks which include digital visualization, simulation modelling and virtual urban scenario development in addition to their traditional tasks like mapping, data storage and comparative analysis. However, despite the widespread application of digital tools in city planning and urban design, caution is warranted so that these technologies remain an aid rather than a substitute for the experienced planner and intuitive designer (Cheshmehzangi, 2025). The digital transformation of cities and smart urban development requires thorough analysis because smart-city systems tend to focus on operational efficiency at the expense of human experience unless developers establish proper guidelines (Townsend, 2014; Batty, 2018). Scholars warn that algorithmic governance, sensor-driven optimization, and predictive modelling may inadvertently reinforce technocratic decision-making, reduce civic agency, or oversimplify urban complexity (Greenfield, 2013; Sadowski, 2020).

The discussion about sustainable cities has produced multiple new sustainable-city models which present alternative concepts for urban development. The compact city, eco-city, resilient city, sustainable neighbourhood and 15-minute city approaches work to link environmental sustainability with community well-being (Newman & Kenworthy, 1999; Moreno, Gehl and Thorne, 2024). The deployment of these technologies produces unequal results because they maintain the same technological optimism that drives much of contemporary digital urbanism.

In an era where sustainability is becoming an urgent priority, there is a growing need for different perspectives that break away from the “silo mentality” often found within disciplines involved in urban development (Keivani, 2009). Lehmann’s (2010) ideas on creating sustainable cities begin with the imperative to “rethink the city itself,” incorporating criteria such as energy use, waste, and patterns of food and water consumption. Building on this foundation, Lehmann and Crocker (2012) emphasize the need for a robust understanding of the relationships between lifestyle, consumption, technology, and urban development. The study of vernacular practices needs to be studied as a vital field which goes beyond being considered outdated or a nostalgic exercise; nor should the romanticization of advanced technologies and their often-costly implementation be viewed as the sole pathway toward sustainable urban planning and design in the 21st century. Given the complexity of contemporary urban challenges and the evolving attempts to define what constitutes a sustainable city, scholars increasingly recognize that no single urban form can be universally applied. Rather, as Williams et al. (2000) suggest, multiple sustainable urban forms may exist, each capable of responding to its specific cultural, environmental, and socio-economic context.

3. From Static Cities to Living Systems: The Concept of “Breathing Cities”

In light of this emerging perspective, Cheshmehzangi (2025) looks at how cities can develop amid environmental, economic, and spatial constraints by drawing on ingenuity, local knowledge, and innovative design. Cities can build resilience through basic methods which do not need sophisticated technology or revolutionary scientific discoveries, by using adaptive reuse with circular thinking and participatory governance systems. According to Cheshmehzangi urban “resourcefulness” involves not only achieving more with fewer resources. But also transforming social values toward relationships, materials, ecosystems and lived experience, elements that collectively shape more resilient and context-responsive urban environments (Cheshmehzangi, 2025). Designing healthy cities requires far more than applying fixed spatial

solutions to current environmental challenges. As noted by Cheshmehzangi et al. (2025) this calls for proactive, forward-thinking design strategies that enable cities not only to adapt to climate impacts but also to meaningfully reduce them. This transformation shows a broader move toward anticipatory, human-centered, and ecologically grounded urbanism.

This work establishes "breathing cities" as a new urban design concept which transforms current urban planning approaches. The operation of breathing cities depends on independent urban systems which use adaptable designs that unite environmental sustainability with flexibility instead of using rigid control systems and strict structures. They integrate vernacular knowledge with digital spatial technologies, emphasizing health-centered design, environmental sustainability, and social equity.

Key principles of the “breathing cities” framework include:

- **Cities as adaptive ecosystems**: Urban systems should respond dynamically to environmental, social, and technological changes.
- **Integration of tradition and technology**: Combining local, vernacular strategies with digital tools fosters resilient and context-sensitive design.
- **Health-centered urbanism**: Urban planning must prioritize human and ecological well-being, integrating green spaces, clean air, and active mobility.
- **Scalable, context-sensitive solutions**: Solutions should be replicable across diverse climates and socio-cultural contexts.

By treating cities as living systems, the framework challenges conventional engineering-driven approaches. It also advocates for co-evolution between the built environment and ecological processes.

4. Methodology

The work uses a qualitative, comparative case study approach to examine real-world systems influenced by multiple factors. This research method enabled authors to do an in-depth exploration of underlying motivations, institutional frameworks, and potential outcomes (Yin, 2018). Case studies were chosen based on their varied climates, cultural contexts, and sustainability strategies, ranging from low-tech vernacular systems and advanced digital urban models. The study analyses cities such as Singapore, which combines nature-based design and digital governance, Copenhagen, a leader in blue-green infrastructure and carbon-neutral planning, and two experimental cities, Masdar City and The Line, which use AI systems and renewable technologies. In parallel, historical and vernacular urban models such as Yemen and Morocco are studied for their emphasis on passive climatic adaptation, spatial porosity, and material resilience. The methodology connects vernacular strategies with contemporary digital tools to explore adaptive design solutions. Analytical criteria focus on ecological responsiveness, climate adaptation, social equity, technological integration, and scalability. This multi-layered approach provides insights into how different urban contexts can effectively adopt “breathing cities” principles. The research develops a method which combines historical and present-day practice analysis with forward-looking urban design direction.

5. Case Studies: From Vernacular Ecologies to Data-Driven Cities

5.1 Vernacular Urbanism: Shibam and Marrakech

The cities of Shibam in Yemen and Marrakech in Morocco (Fig.1) demonstrate how historical cities implement their cultural heritage and natural environment to develop climate-friendly designs through their established urban planning techniques. The desert town of Shibam is known as the "Manhattan of the desert" because it contains multi-story mudbrick buildings arranged in a dense, vertical layout. This compact morphology protects its interior from desert sunlight while it generates its own shade and allows wind to flow through the space which shows advanced methods for cooling buildings and controlling local climate conditions (Abu-Lughod, 1987). The city of Marrakech protects its residents from heat through its narrow streets which follow winding paths to create courtyards that provide ventilation and privacy. Construction projects that use locally obtained materials including adobe and stone achieve improved thermal control because these materials enable buildings to respond to temperature changes throughout different seasons (Gil-Piqueras and Rodríguez-Navarro, 2021).



Figure 1. Left: Shibam, Yemen "Manhattan of the desert". Right: Marrakech, Morocco. Narrow streets for shading and courtyards for passive cooling. Source: Internet.

These vernacular models highlight spatial porosity, material resilience, and energy-efficient passive strategies, providing lessons in sustainable urban living that require minimal technological intervention. Beyond environmental adaptation, their designs foster social cohesion and human-scale interaction. Public spaces and communal courtyards support daily activities while remaining well adapted to the climate. The current urban planning practices which implement these principles could develop sustainable cities through the combination of historical wisdom with modern sustainability targets.

5.2 Singapore: Nature-Based Urbanism and Digital Integration

Singapore has become an example of how sustainable urban innovation can transform a city. Once a resource-scarce island with few natural advantages, it is now recognized as a world leader in urban greening (Tan et al., 2021). Urban designers in Singapore now use nature-based solutions that employ natural systems to address climate change (Nesshöver et al., 2017). The implemented strategies consist of green and blue infrastructure which combines natural and semi-natural and man-made elements with ecological engineering methods that unite human-made spaces with ecological systems (Nesshöver et al.,2017). The city demonstrates effective digital governance through its deployment of environmental sensors and smart monitoring systems which improve its operations for energy efficiency and water management and waste reduction. Singapore achieves better urban sustainability through its combination of ecological design with digital technology which creates more comfortable cities and stronger urban systems (Fig.2: Left). The government implements its sustainable development plans through the Singapore Green Plan 2030 which serves as a national ten-year initiative for environmental sustainability. The plan establishes specific targets to reach net-zero emissions during 2050 through its five fundamental pillars which include City in Nature, Energy Reset, Sustainable Living, Green Economy and Resilient Future (Singapore Green Plan 2030). Singapore has become a worldwide example of sustainable urban development through its implementation of ecological design and digital technologies and its government-led policy initiatives.



Figure 2. Left: Gardens by the Bay, Grant Associates, Singapore. Singapore Green Plan 2030 - City in Nature. Right: Copenhagen, Denmark. A Model for Sustainable Urbanism. Source: Internet.

5.3 Copenhagen: Blue-Green Infrastructure and Climate Neutrality

Copenhagen leads the world as the top destination for blue-green infrastructure and climate-neutral urban planning because it became the first operational "sponge city" in the world (The World Economic Forum, 2025). The city implements nature-based solutions through its water management and urban resilience strategies which use permeable surfaces, green roofs, rain gardens and stormwater management systems. The implemented interventions help protect against flooding while they work to decrease urban heat island temperatures and support local wildlife and establish community areas which make cities more habitable (Ahern, 2011; Kabisch et al.,2017). The city of Copenhagen achieves its success through three main

elements which include policy frameworks, community engagement and digital technologies (Fig.2: Right). The city operates smart monitoring systems which provide real-time environmental data to achieve maximum water management efficiency while tracking sustainability outcomes to confirm that all communities receive benefits from its interventions and continue to develop (Jabareen, 2013; The World Economic Forum, 2025). The method proves adaptive urbanism which demonstrates that cities can achieve climate neutrality between 2025 and 2030 by uniting their ecological, social and technological objectives (Copenhagen Municipality, 2020). The city of Copenhagen demonstrates an effective approach which other municipalities can use to build sustainable urban environments through climate adaptation initiatives.

5.4 Masdar City and The Line: AI-Driven Urbanism

Masdar City in Abu Dhabi and the Line in NEOM, Saudi Arabia, are two of the Gulf's most ambitious urban experiments, showcasing innovative approaches to sustainable development and the integration of advanced technologies (Fig. 3). These designs function as experimental models which will guide upcoming urban development through their connection between population expansion, environmental conservation and technological progress. Their research has received international recognition because it demonstrates how their home nations can enhance their strategic position through studies about sustainability and technological advancement and economic diversification (Kashef, 2025). The low-carbon urban experiment of Masdar City operates at maximum efficiency through its AI-driven infrastructure which combines with smart energy grids and real-time environmental monitoring systems for energy, water and waste management (Reiche, 2010).



Figure 3. Left: Masdar City, UAE, Foster + Partners. Pioneering a sustainable urban community. Right: The Line, Saudi Arabia. Linear, car-free, zero-carbon city. Source: Internet.

Renewable energy, particularly solar power, is central to its design, and intelligent systems regulate daily urban functions, demonstrating how technology can enhance efficiency while reducing the city's carbon footprint. Similarly, The Line presents an extreme urban design concept which envisions a 170-kilometer linear city that operates through artificial intelligence control of its infrastructure and uses only renewable power sources (NEOM, 2021). Designed to reduce commuting times, optimise density and protect surrounding landscapes, it reflects a strong commitment to efficiency and environmental responsibility. Envisioned as interconnected cognitive communities, the Line aims to use artificial intelligence to deliver a pollution-free, car-free urban environment with enhanced quality of life (Al-Sayed et al., 2022). The two cities show how digital technology supports the creation of sustainable high-performance urban areas

which focus on climate protection. Together, these examples show that while AI and digital systems can make cities more efficient and environmentally friendly real sustainability is about more than just technology. The objective requires finding the right balance which connects technological components to natural environments and human activities.

6. Discussion

The comparative analysis of the case studies shows that there is no single path to sustainable urbanism. Each city takes its own approach, shaped by local needs, resources, and values. The cities of Shibam in Yemen and Marrakech in Morocco demonstrate vernacular city planning through their use of passive climatic adaptation, spatial porosity and material resilience to develop sustainable designs which support human needs and environmental health. In contrast, technologically driven cities, including Masdar City, The Line, Singapore, and Copenhagen, demonstrate how AI, IoT, digital twins, and smart monitoring systems can enhance urban resilience, optimize resource use, and support climate-adaptive governance. When traditional wisdom is combined with modern digital tools, cities have a genuine opportunity to adapt and flourish. By valuing the lessons of the past while exploring what is possible today, urban environments can respond more effectively to the complex challenges of the contemporary world.

This research reveals that breathing cities achieve their greatest benefits through the combination of vernacular strategies and digital innovations, producing positive outcomes for environmental sustainability, social development, and technological progress. The environmental benefits of cities emerge from using traditional building methods that combine passive cooling systems with porous building designs and durable materials, while smart monitoring systems track energy consumption, water usage and waste management. Cities can address their climate and environmental challenges by implementing contemporary infrastructure solutions together with their historical architectural features. Socially breathing cities focus on designing spaces which prioritize the needs of their citizens. The process of urban development becomes more equitable because inclusive planning and community engagement work to solve hidden environmental injustices which create social equality and build stronger community bonds.

Digital tools enable planners to respond better to resident needs through their ability to deliver instant data about how people use services and access them and how resources get distributed. The cities demonstrate how real-time monitoring systems with AI technology and data-based decision processes create better resilience and operational efficiency and flexible responses to changing conditions. Smart infrastructure systems enable better energy management and enhanced water resource control and environmental threat prediction through its operation which draws knowledge from traditional urban planning methods. The research results establish vital criteria which need to guide policy development. Planners and policymakers must implement integrated vernacular-digital approaches because sustainable urban development needs methods which connect environmental protection with social needs and technological advancement. The discussion demonstrates that cities need a holistic, multi-layered urban design framework that responds to contemporary global challenges while promoting equitable, resilient, and adaptive cities.

7. Conclusion

This study addressed the critical question of how contemporary cities can navigate environmental, social, and technological challenges while moving toward more sustainable and resilient futures. Key findings indicate that cities can grow sustainably by bridging indigenous urban knowledge with emerging

technologies. The comparative analysis of selected case studies revealed a wide range of historical sustainability strategies, demonstrating that, while the mediums and tools may change over time, the underlying ideas form a rich and enduring tapestry of adaptive urbanism. This work introduced the "breathing cities" framework as a conceptual model aimed at fostering more resilient, equitable, and climate-sensitive urbanism. The framework is not conceived as a rigid set of prescriptive design rules. Instead, it serves as a structured interpretative tool to inform and guide urban analysis, planning strategies, and design decision-making. It can be translated into actionable directions for planners by identifying key principles, including adaptive use of local knowledge, technological integration, and environmental responsiveness. These principles may be operationalized as context-sensitive planning guidelines rather than universal design codes. At the same time this study acknowledges several limitations that must be considered when applying this framework. First, integrating vernacular knowledge with advanced digital technologies can be challenging due to gaps in expertise, data availability, and institutional capacity. Second, the framework's reliance on technology risks exacerbating inequalities if access to digital tools is uneven. Third, translating context-specific vernacular strategies to different cultural and climatic settings may reduce their effectiveness without careful adaptation. Finally, while the framework emphasizes holistic design, practical implementation depends on political will, governance structures, and financial resources, which may limit its scalability and long-term impact. Future research into "breathing cities" should look at how to apply the framework to individual cities across the globe, incorporating the latest technologies, such as AI, IoT and digital twins to enable real time monitoring and analysis of buildings and cities. Historical vernacular strategies of buildings should be analysed through a combination of analytical and projective methods to inform resilient and context sensitive interventions into urban environments. This will allow for sustainable, equitable and adaptable environments that are able to respond to local circumstances. "Breathing cities" challenges the artificial separation of city and nature by reading urban space as part of a larger planetary system.

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