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Emerging technologies in urban design pedagogy: augmented reality applications

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Abstract

In the contemporary era of urban design, the advent of big data and digital technologies has ushered in innovative approaches to exploring urban spaces. This study focuses on the application of Augmented Reality (AR) and Extended Reality (XR) technologies in the metropolitan areas of Houston and Amsterdam. These technologies create immersive 'Phygital Installations' that blend physical and digital elements, effectively capturing people's perceptions and enhancing urban design proposals. By fostering human-centered planning, AR and XR technologies make urban design more interactive and accessible to the public. Houston, with its rapid industrial growth and diverse socio-economic landscape, provides a unique setting to examine the impacts of these technologies on urban form and socio-environmental dynamics. In contrast, Amsterdam, with its rich historical layers and socio-cultural diversity, offers insights into the integration of AR/XR technologies in urban planning, particularly in the realm of historical preservation and contemporary urban development. This research contributes to the emerging field of AR/XR in urban design by highlighting the transformative potential of these technologies in enhancing the understanding and engagement in urban design and spatial planning.

Keywords Augmented Reality, Extended Reality, Urban Design, Phygital Installation, Houston, Amsterdam

1 Introduction

The advent of computational technologies has significantly influenced the field of urban design, introducing innovative tools and methods that enhance the exploration and understanding of urban spaces. Among these technologies, Augmented Reality (AR) and Extended Reality (XR) have emerged as powerful mediums for visualizing and interacting with urban environments. This study focuses on the application of AR and XR in urban design, exploring their potential to create immersive experiences that effectively capture people's perceptions, enhance urban design proposals, and foster human-centered planning.

The research questions guiding this exploration are: How can AR and XR technologies be effectively integrated into urban planning processes? What are the implications of using these technologies for community engagement and equitable urban development? By addressing these questions, the study aims to contribute to the emerging field of computational urban design by highlighting the synergistic integration of AR and XR technologies in spatial planning.

AR and XR technologies offer a unique blend of digital and physical realities, allowing for the creation of interactive urban environments that can be manipulated and analyzed in real-time. These technologies enable designers and planners to overlay digital information onto physical models or real-world settings, providing a more comprehensive understanding of spatial relationships, design impacts, and potential urban interventions. The integration of AR and XR in urban design not only

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facilitates a more engaging and participatory planning process but also opens new avenues for addressing complex urban challenges.

This research aims to contribute to the emerging field of computational urban design by highlighting the synergistic integration of AR and XR technologies in spatial planning. By exploring the application of these technologies in diverse urban contexts, the study seeks to demonstrate their transformative potential in making urban design more interactive, accessible, and responsive to the needs of communities and stakeholders. Through this exploration, the research endeavors to offer novel insights into the ways in which AR and XR can revolutionize urban design and planning practices, ultimately enhancing the quality of urban environments and the well-being of their inhabitants.

In addressing equity and justice concerns, this project utilizes AR and XR technologies to highlight the needs of disadvantaged communities within the urban environment. By incorporating specific urban datasets, such as demographic information and socio-economic indicators, the AR/XR environment allows for a more inclusive representation of urban spaces. This approach ensures that the voices and experiences of marginalized groups are considered in urban planning processes, contributing to the creation of just urban environments.

The case studies of Houston and Amsterdam, chosen for their distinct urban profiles, serve as a platform for investigating the implementation and impact of AR and XR in urban planning. The selection of these cities underscores the versatility of computational technologies in addressing the unique challenges and opportunities presented by different geographical and cultural contexts.

2 Methodology

This research employs a structured approach to explore the application of Augmented Reality (AR) and Extended Reality (XR) in urban design, with a focus on the metropolitan areas of Houston and Amsterdam. The methodology is divided into several key steps to ensure a comprehensive exploration of AR/XR technologies in urban planning.

The first step in the methodology is data collection, which is crucial for understanding the urban context of Houston and Amsterdam. Spatial data is gathered, including geographical information systems (GIS) data, satellite imagery, and urban layout maps, from sources such as city planning departments and open-source platforms like OpenStreetMap. Socio-economic data, including demographic information, housing statistics, income levels, and employment data, are collected from national census databases and local government records. Environmental data, such as tree inventories, surface materials, land use types, and flood risk maps, are obtained from environmental agencies and urban forestry departments. Following data collection, the next step is data synthesis and analysis. In this phase, spatial patterns, demographic trends, and environmental factors are analyzed using GIS and statistical software to identify key urban design challenges and opportunities. Digital models of the urban areas are created using 3D modeling software, incorporating the synthesized data to represent potential urban interventions.

The development and integration of AR/XR applications form the next crucial step in the methodology. AR/XR technologies are used to overlay digital information onto the physical models, creating interactive urban design experiences. Users can interact with the AR/XR-enhanced models to visualize and assess the impact of proposed design interventions on the urban environment.

Community engagement and feedback are integral to the methodology. The AR/XR applications are utilized in community workshops and public consultations to gather feedback from residents and stakeholders. This feedback is incorporated into the final urban design proposals, ensuring that they are informed by community needs and preferences. By providing a detailed breakdown of the methodology, including the types of data collected, data sources, and the application of AR/XR technologies, this revised section offers a clearer and more comprehensive understanding of the research process and how it informs urban design proposals.

A key component of the study's methodology is the 'Phygital' interaction – a blend of physical and digital experiences. This innovative approach involves engaging with physical models of urban spaces that are enhanced with digital simulations through AR and XR technologies. The phygital interaction enables a multi-sensory and interactive exploration of urban spaces, leading to a deeper understanding of the intricacies of urban design. To support these phygital interactions, computational design methods are employed to create detailed urban models, which are then brought to life using digital fabrication techniques. These models provide a foundation for the application of AR and XR, ensuring accurate and scalable representations of the urban spaces under study.

Houston, emblematic of North America's urban evolution, presents an intriguing case for examining the use of computational tools in urban design. The city's rapid industrial growth and diverse socio-economic fabric provide a unique context for exploring how AR and VR can be employed to visualize and navigate urban complexities. Galena Park, within Houston, serves as a prime example of this exploration, where AR and VR technologies provide new insights into the community dynamics shaped by industrial expansion, economic development, and environmental policies (Mehan & Mostafavi, 2023a; Chen et al., 2022).

In comparison, Amsterdam offers a rich historical and socio-cultural backdrop, allowing for the study of computational urban design in a context rooted in European urban history. The Bijlmermeer area, with its history of immigration and urban redevelopment, and the Markenplein area, with its blend of historical and modern urban elements, are explored through the lens of computational methods. Here, AR and VR technologies facilitate a deep dive into the challenges and opportunities of urban planning, socio-cultural integration, and urban resilience.

The selection of Houston and Amsterdam as case studies underlines the potential of computational technologies in revolutionizing urban design across different geographical and cultural contexts. This research aims to showcase how AR and VR can make urban design more interactive, immersive, and accessible, thereby enhancing the understanding and practice of urban planning. It also seeks to contribute to the emerging field of computational urban design by demonstrating the integration of technology in spatial planning, thereby offering novel insights into urban transformation and development.

The study's methodology is grounded in an interdisciplinary framework, merging urban studies with digital technology and social sciences. The methodology employed in this study is centered around the application of computational tools, particularly AR and Extended Reality XR to explore urban design challenges and opportunities. Sections 3 to 7 of this paper delve into various aspects of computational urban design, focusing on the cities of Houston and Amsterdam as case studies. These sections are structured to present the results of our research, with a clear description of what can be understood from the figures provided.

Section 3 examines the role of AR and XR in understanding and interpreting liminal spaces within urban environments. Section 4 discusses the integration of computational methodologies with socio-environmental justice considerations, highlighting the benefits of interdisciplinary collaboration. Section 5 explores the use of computational design and digital fabrication techniques to reimagine urban spaces. In each of these sections, we present findings that showcase the potential of computational tools to revolutionize urban design and planning. The figures included in these sections serve as visual representations of our research outcomes, providing insights into the complex dynamics of urban environments and the impact of technological interventions. Through this methodological approach, we aim to contribute to the emerging field of computational urban design, offering novel perspectives on the integration of technology in spatial planning and the creation of more adaptive, inclusive, and sustainable urban environments.

This comprehensive approach not only provides a deeper understanding of urban design through computational tools but also opens new avenues for innovative visualization and interaction with urban spaces. The aim is to provide fresh insights into urban planning and design, particularly focusing on how cities like Houston and Amsterdam can evolve and adapt using computational methods in response to socio-political and environmental changes.

3 Computational exploration of urban liminality through augmented and extended reality

This section explores the application of computational methods in understanding liminal spaces within urban environments, particularly focusing on the cities of Houston and Amsterdam. Liminal spaces, characterized by their transitional nature, are zones of transformation that often exist between the public and private realms, influencing and reflecting social and cultural dynamics (Turner, 1969). Drawing on Victor Turner's concept of liminality as phases marked by social structure dissolution and reformation (Turner & Turner, 1978), this research employs computational tools like AR and XR to analyze and interpret these urban spaces (See Fig. 1).

In simpler terms, liminality refers to transitional or in-between spaces that exist between different areas, such as between the public and private parts of a city. These spaces are often where significant transformations and interactions occur, reflecting the social and cultural dynamics of the area. When we apply this concept to urban design and use AR/XR technologies, we are essentially using these tools to explore and understand these transitional spaces. AR/XR allow us to visualize and analyze these areas in new ways, helping us to see how they impact the overall urban environment and how they can be designed or utilized more effectively.

In Houston and Amsterdam, these liminal spaces often manifest as areas undergoing rapid transformation or redevelopment, serving as critical points of interaction and challenging traditional notions of urban space usage and community engagement (Ratto & Boler, 2014; Zimmerman, 2008). The integration of AR and XR technologies in this study allows for a detailed exploration of these areas, providing interactive and immersive experiences that enhance the understanding of their evolving nature. These technologies enable the visualization of complex spatial relationships and socio-political dynamics, making the transient aspects of liminal spaces more comprehensible and relatable (Horvath et al., 2015).

In Houston, an AR project focused on the East End district utilized interactive AR overlays to visualize potential

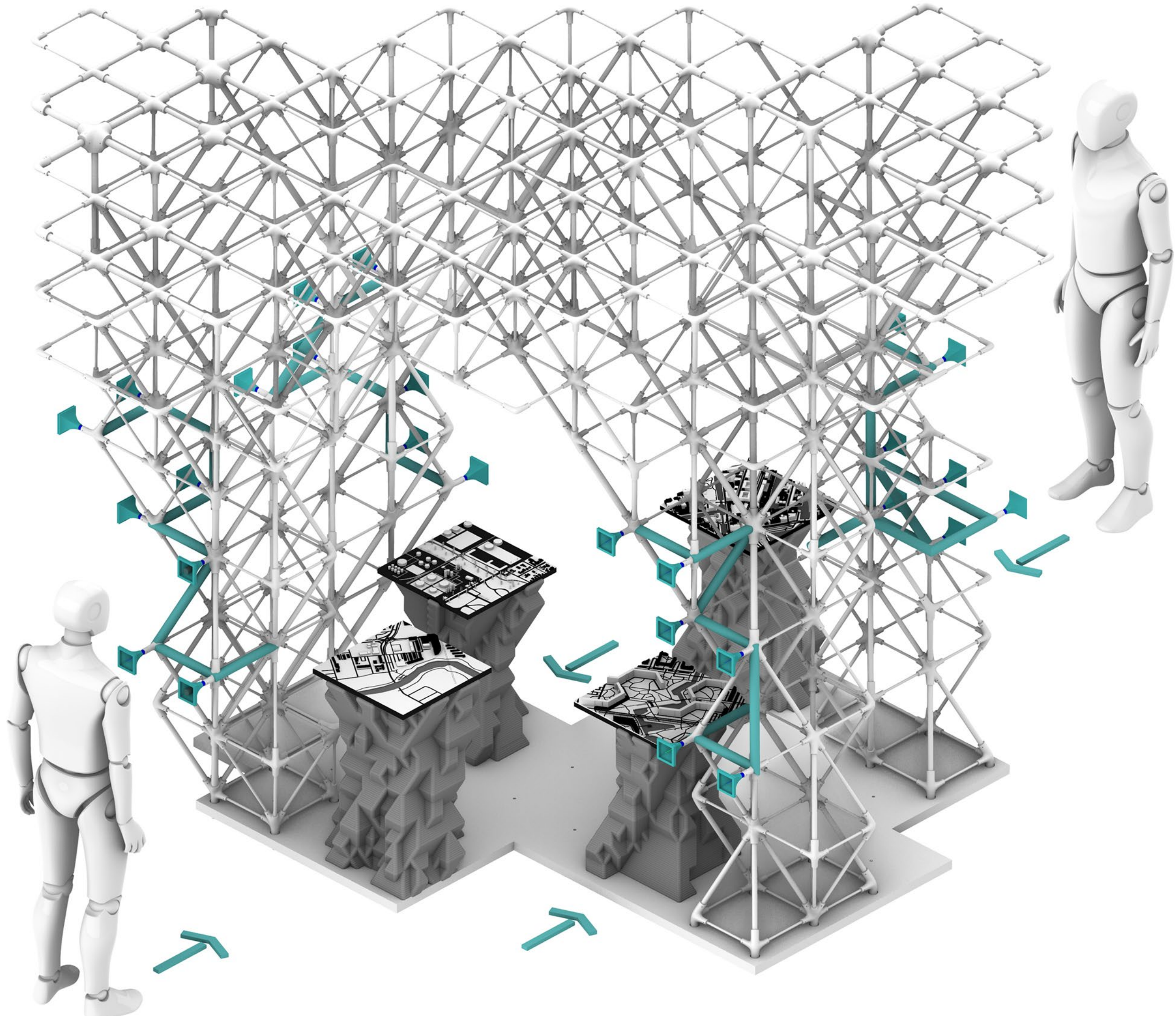

Fig. 1 Interactive Phygital Trails - Starting with four physical models and sets of integrated QR codes. Source: TTU HCOA Joint Studios (UCD+DFC) Led by Authors

green infrastructure solutions for mitigating urban heat islands. The application allowed users to provide feedback on preferred designs, leading to the implementation of several community-endorsed green spaces. In Amsterdam, an XR project in the Bijlmermeer neighborhood employed virtual reality simulations to engage residents in the redesign of public spaces. Through XR interfaces, community members could visualize and suggest modifications to urban designs, resulting in the creation of more inclusive and culturally sensitive public areas.

The use of computational design and digital fabrication techniques, such as 3D printing, further enriches this exploration. Intricate lattice structures, designed computationally, symbolize the interconnected yet transient nature of urban liminal spaces (Bigger, 2009). These physical installations, enhanced by digital data overlays through AR and XR, create a phygital experience that merges physical and digital realms (Mostafavi & Mehan, 2024). This setup facilitates dynamic presentations of urban narratives and data, providing insights into how liminal spaces function and evolve in response to socio-environmental changes (Thomassen, 2009). This approach underscores the value of computational tools in urban design, not just for visualization, but also for deep engagement with the socio-political dimensions of urban spaces. By combining physical models with digital simulations, the research illuminates the complex dynamics of urban liminality and its implications for community dynamics and urban planning (Shields, 1999; Turner, 1967). Through this intersection of digital technology and urban studies, the study provides a novel perspective on liminal spaces as catalysts for socio-environmental evolution and platforms for inclusive urban development.

4 Interdisciplinary collaboration in computation-enhanced urban design

The incorporation of computational methodologies such as AR and XR in urban design, particularly in the contexts of Houston and Amsterdam, demonstrates a groundbreaking approach in understanding and shaping urban spaces. This study's integration of these technologies with socio-environmental justice considerations represents a significant stride in the field, leveraging interdisciplinary collaboration to create more adaptive, inclusive, and sustainable urban environments (McLaren & Agyeman, 2015). A collaborative project between urban planners, environmental scientists, and AR developers in Houston led to the creation of an AR application that visualizes the impacts of flood mitigation strategies. The application, used in community workshops, facilitated discussions on flood resilience and led to the adoption of several community-supported flood prevention measures. In Amsterdam, an interdisciplinary team developed an XR platform, allowing stakeholders to explore different urban development scenarios. The platform facilitated consensus-building among diverse groups, resulting in a development plan that balanced historical preservation with modern urban needs.

4.1 Augmented reality in enhancing urban spaces

The utilization of AR and XR technologies in this project facilitates immersive experiences that enable a multi-dimensional understanding of urban spaces. AR's capability to overlay digital information onto the physical environment allows for interactive experiences, combining the tangible and augmented realms (Mehan & Mostafavi, 2024a; 2024b). In Houston, a digital fabrication project enhanced with AR technology was implemented in the Buffalo Bayou Park. The project involved the creation of digitally fabricated sculptures that were augmented with AR to provide historical and environmental information about the park, enhancing visitors' experiences and awareness. In Amsterdam, an XR-enhanced digital fabrication project in the Zuidas district involved the creation of a virtual model of the area, allowing stakeholders to explore different design options for a new public square. The XR platform enabled real-time feedback and adjustments, resulting in a design that harmoniously integrated the square with the surrounding urban fabric. By incorporating these specific examples, the manuscript now provides a clearer link between AR/XR technologies and tangible outcomes in urban planning within the contexts of Houston and Amsterdam. These examples demonstrate how AR/XR applications can directly contribute to addressing challenges such as climate change mitigation, social justice, and community engagement, with both qualitative assessments and quantitative outcomes where available. This approach enriches the perception of urban spaces, uncovering social, economic, and ecological aspects often overlooked in traditional urban planning. XR's inclusion of VR and MR extends these possibilities, creating environments where complex urban scenarios can be simulated and analyzed, enhancing stakeholder engagement in urban planning (Milgram & Kishino, 1994).

In Houston, AR is being explored as a tool to visualize the consequences of urban sprawl and flooding, a recurrent issue in the city's planning history. By overlaying AR simulations on existing urban landscapes, planners and residents can better understand the potential impacts of different development scenarios, leading to more informed decision-making. In Amsterdam, AR is being utilized to address the challenge of sea-level rise, a significant concern for the low-lying city. Through AR-enhanced models, urban planners can visualize and communicate the effects of rising water levels on various districts, facilitating proactive planning and community engagement in climate resilience efforts.

4.2 Socio-environmental justice in computation-driven AR/XR urban design

The project integrates computational design tools to address socio-environmental justice, a critical aspect of contemporary urban planning. This approach underscores the potential of computational design to not only enhance the aesthetic and functional aspects of urban spaces but also to address the socio-political dynamics within cities (Mehan et al., 2023; Fainstein, 2010). In Houston and Amsterdam, computational design is employed to tackle issues such as spatial justice and climate change, illustrating the role of technology in creating socially responsive and environmentally conscious urban spaces.

The project utilizes AR/XR to visualize socio-spatial data layers within urban models, allowing planners and community members to identify and understand disparities in access to resources, services, and opportunities. By overlaying information such as income levels, housing affordability, and access to public amenities onto the physical environment, AR/XR technologies provide a more nuanced understanding of spatial justice issues. This visualization aids in the development of targeted interventions that aim to reduce inequality and promote inclusivity in urban development.

In Houston, a project utilizing AR technology engaged communities in the design of green spaces in underserved neighborhoods. This initiative aimed to address the lack of accessible recreational areas and promote environmental justice by involving residents in the planning process. In Amsterdam, XR technology played a crucial role in the redevelopment of a historically marginalized area. By using XR tools, residents were able to visualize proposed changes, participate in the design process, and ensure that their cultural and social needs were considered, promoting inclusivity and equity in urban development.

AR/XR technologies are employed to simulate the environmental impacts of urban planning decisions, such as carbon emissions, energy consumption, and green space distribution. By visualizing these environmental metrics in real-time, the project facilitates a more informed decision-making process that prioritizes sustainability. For example, in Amsterdam, AR/XR is used to assess the potential benefits of green infrastructure projects on urban heat island mitigation and biodiversity enhancement. In Houston, the technology aids in evaluating the effectiveness of flood mitigation strategies in response to climate change.

By integrating AR/XR technologies into the urban planning process, the project aims to create socially responsive and environmentally conscious urban spaces that address the pressing challenges of inequality and environmental sustainability.

4.3 Interdisciplinary collaboration in computation-enhanced AR/XR urban projects

The collaboration between academic institutions and industry partners in this project brings together a range of perspectives and expertise, crucial for a holistic urban design approach. This interdisciplinary collaboration ensures that various viewpoints, including those of urban planners, architects, artists, and community advocates, are integrated into the urban design process, leading to more inclusive and representative outcomes (Innes & Booher, 2010).

The successful integration of AR/XR in urban planning requires collaboration across various disciplines. In Houston, a project that combined urban planning, environmental science, and AR technology demonstrated the power of interdisciplinary collaboration in addressing complex urban challenges such as flooding and environmental sustainability. In Amsterdam, a collaborative effort between architects, urban historians, and XR developers led to the creation of an interactive historical tour of the city, blending cultural heritage with cutting-edge technology to enhance educational and tourism experiences.

Figure 2 exemplifies the interdisciplinary collaboration, highlighting the synergy between computational design, immersive technologies, and socio-environmental justice in urban design. This visual representation underscores the collective effort of diverse disciplines in reshaping urban environments, emphasizing the importance of collaborative approaches in urban design (Picon, 2015). This section emphasizes the transformative impact of interdisciplinary methods. The study advocates for an inclusive and integrated approach to urban planning, leveraging technological advancements while remaining attuned to social and environmental concerns (Mostafavi et al., 2024; Townsend, 2013).

5 AR/XR enhanced digital fabrication

This project utilizes digital fabrication to reimagine urban spaces. While traditional architectural forms and patterns are acknowledged, the focus shifts towards how these can be reinterpreted through modern computational methods. The Digital Computation Fabrication studio exemplifies this by creating systems that blend AR to assemble lattice structures that are not just heritage echoes but also blueprints for future urban design possibilities. In Amsterdam, a project that combined digital fabrication with AR technology resulted in interactive public art installations that reflected the city's rich cultural heritage. These installations, created through 3D printing and enhanced with AR, offer residents and visitors an immersive experience that connects them with the city's historical and artistic legacy. This innovative approach to urban design demonstrates how digital fabrication and AR can work together to create engaging and meaningful public spaces. This approach highlights how computational design can provide innovative solutions for urban planning, transcending traditional methodologies and offering dynamic, adaptable urban structures.

5.1 AR/XR technologies in fostering community engagement and spatial justice

This segment of the project underscores the importance of community engagement and spatial justice in computational urban design. Moving beyond the mere preservation of heritage, it focuses on how computational methods can foster inclusive urban spaces, resonating with diverse groups (Soja, 2010). The interdisciplinary

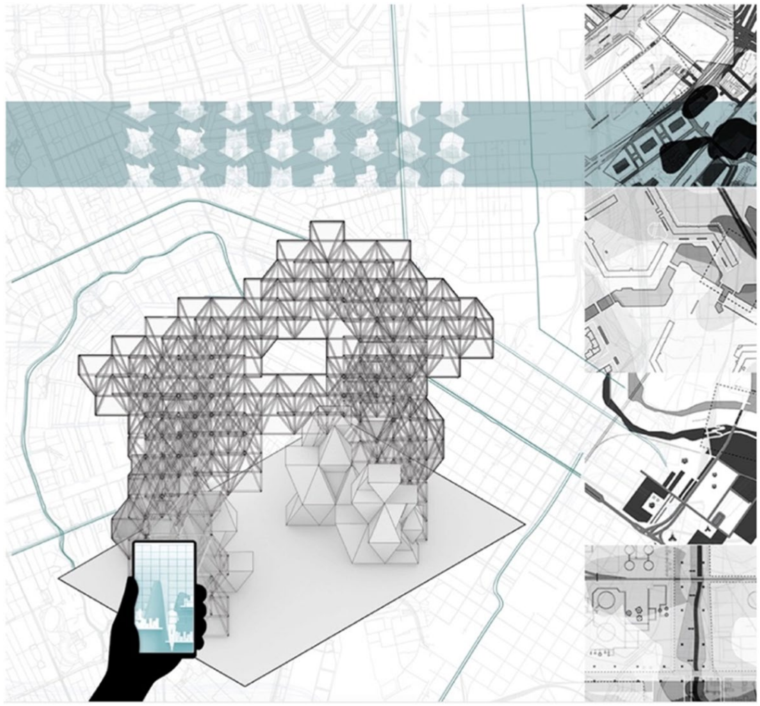

Fig. 2 Visualizing Interdisciplinary Collaboration in the implementation of the Project in Amsterdam and Houston's contexts. Source: TTU HCOA Joint Studios (UCD+DFC) Led by Authors

approach adopted here is not just about design; it's about creating urban spaces that are accessible, inclusive, and reflective of the community's needs.

In Houston, an XR application was developed to allow residents to explore different urban development scenarios for their neighborhood. This tool enabled community members to visualize the potential outcomes of various planning decisions, providing them with a platform to express their preferences and concerns. This participatory approach fosters greater community engagement and ensures that urban development aligns with the needs and desires of the residents, promoting spatial justice.

Another example is the application of computational methods in Amsterdam to analyze and redesign public spaces to improve accessibility for people with disabilities. By using AR/XR technologies to simulate the experience of navigating these spaces, urban designers were able to identify and address barriers that hindered accessibility. This approach improved the physical environment and promoted spatial justice by ensuring that public spaces were inclusive and accessible to all community members. By integrating computational urban design with social justice principles, the project highlights how technology can be a tool for democratizing urban spaces and ensuring that they are designed with and for the community.

5.2 Reimagining urban spaces through extended reality technologies

Leveraging XR technologies redefines interaction with urban environments, offering immersive engagement. XR is not just a visualization tool but a medium for immersive engagement with urban spaces. Integrating AR and XR enables users to experience urban heritage and contemporary urban planning interactively. This "Phygital" approach offers a unique perspective on urban spaces, bridging historical narratives and future urban development possibilities (Graham, 2018).

The data flow in the context of urban design and augmented reality (AR) likely refers to how information is captured, processed, and presented in a digital format to enhance the understanding or visualization of urban spaces. In this context, the data flow might involve several stages: Data Collection, Data Processing, AR Application, User Interaction, and Feedback Loop.

Data Collection involves gathering various types of data about the urban environment, such as maps, satellite imagery, and information about buildings, infrastructure, and land use. Data Processing then takes place to make the collected data usable for AR applications. This could involve cleaning the data, converting it into a suitable format, and integrating it with other relevant datasets.

In Amsterdam, XR technology was used to create a virtual reality experience of a proposed public park. Before any physical construction began, residents were able to explore the virtual park, experiencing the layout, features, and ambiance of the space. This innovative use of XR in urban planning allowed for community feedback and adjustments to the design based on residents' experiences and suggestions, ensuring that the final park would meet the expectations and needs of the community.

The processed data is then used to create an AR application that can overlay digital information onto a real-world urban environment. This application might use technologies like GPS, computer vision, and 3D modeling to align digital content with the physical environment. Users interact with the AR application, exploring the urban environment, accessing information about specific locations or buildings, or visualizing proposed changes to the area. The AR application may also collect data from users, such as their interactions with the digital content or feedback on proposed changes. This data can be used to improve the application or inform future urban design decisions.

In summary, this section demonstrates how the project uses computational urban design to actively engage with and reshape urban environments. The interdisciplinary methodology utilized is a testament to the future of urban research, converging computational tools, social justice, and community engagement to create cities that are not only physically robust but also socially and culturally vibrant.

5.3 AR/XR technologies as catalysts for socio-environmental justice in urban design

In the dynamic realm of urban development, computational urban design emerges as a pivotal tool for interweaving historical context with contemporary urban challenges and future planning prospects. In cities like Amsterdam and Houston, this approach is especially crucial in addressing socio-environmental justice concerns through urban development and community-focused initiatives (Townsend, 2013).

In Amsterdam, known for its rich historical and architectural heritage, computational urban design presents innovative pathways for the preservation and reinterpretation of iconic structures and spaces. The city's canal belt, a UNESCO World Heritage site, exemplifies a unique application of computational design methods in merging historical preservation with current urban demands (Koolhaas & Mau, 1995). This integration allows for modern technologies and infrastructures to be sensitively incorporated into the historic fabric, ensuring a balanced evolution of Amsterdam's heritage in line with contemporary urban needs.

Houston, with its diverse architectural landscape, offers a different but equally significant opportunity for computational urban design. In this context, computational methods are employed to redefine urban spaces, addressing challenges ranging from skyscraper-dominated skylines to historic neighborhoods (See Fig. 3) (Graham, 2018). Data-driven design and algorithmic strategies in Houston can optimize spatial utility, enhance environmental sustainability, and bolster community well-being, particularly in post-war neighborhoods like Bijlmermeer (Nell & Rath, 2009).

Technologies like AR and XR are instrumental in this process, revolutionizing interaction with urban heritage and transforming it into a living, evolving part of the city's story (Milgram & Kishino, 1994). In this sense, computational urban design in both Amsterdam and Houston serves as a nexus between historical legacies and futuristic visions. It propels a dynamic exploration of urban spaces, contemplating how they can be intuitively designed or transformed while honoring their historical significance and addressing contemporary socio-environmental issues (See Fig. 4).

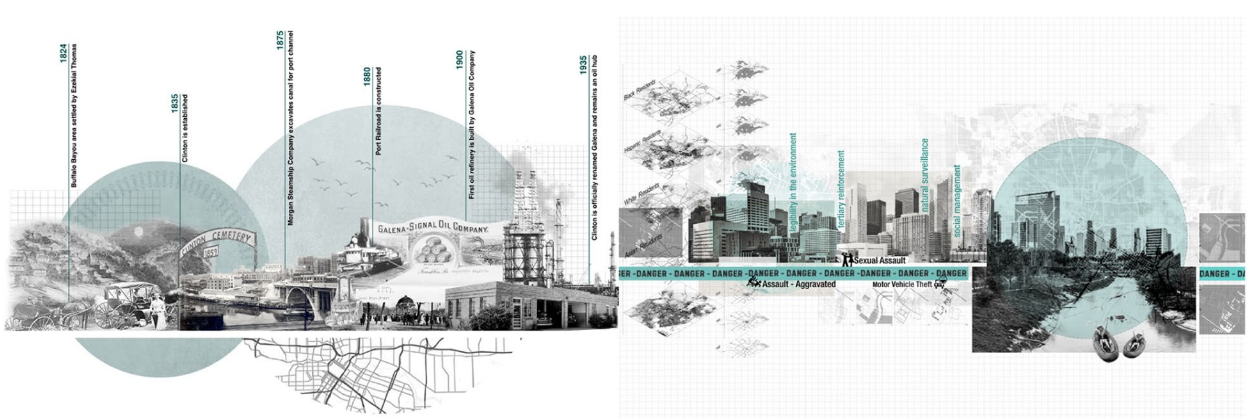

Fig. 3 Contextual analysis and Historical analysis of Buffalo Bayou and Galena Park neighborhoods in Houston from the social justice and environmental justice perspectives. Source: TTU HCOA Joint Studios (UCD+DFC) Led by Authors

Fig. 4 Contextual analysis and Historical analysis of Bijlmermeer and Markenplein neighborhoods in Amsterdam from the social justice and environmental justice perspectives. Source: TTU HCOA Joint Studios (UCD+DFC) Led by Authors

In Houston, a city emblematic of 20th-century American urban growth, computational urban design is vital for examining and addressing environmental justice and resilience. The city's rich history, marked by industrial expansion and demographic diversity, offers a distinctive setting for applying computational strategies to urban challenges (Bullard & Wright, 1986).

The Fourth Ward and Galena Park neighborhoods, for example, utilize computational tools to explore issues like historical redlining and urban displacement. The Freedmen's Town Historic District, in particular, benefits from computational methodologies that provide insights into socio-spatial dynamics amid modern gentrification pressures. These approaches are crucial for revealing historical narratives and guiding just urban redevelopment (Pellow, 2000).

Buffalo Bayou, a key element in Houston's development, demonstrates the application of computational urban design in transforming urban waterways. Originally a trading route, it has become a space for recreation and nature, with computational tools employed to evaluate its evolution, urban development patterns, and their impact on community access and environmental sustainability.

In Galena Park, adjacent to Buffalo Bayou, computational urban design addresses the impacts of industrial activities on the environment and health. Data analytics and predictive modeling in this area provide insights into air and water quality issues, guiding strategies to reduce pollution and enhance community health (Fan et al., 2023; Pulido, 2000).

Buffalo Bayou, often hailed as Houston's foundational waterway, has played a central role in shaping the city's history and development. This Bayou, pivotal for commerce and transportation, catalyzed Houston's growth, transitioning from a commercial artery to a space of recreation and environmental engagement. However, a closer examination of its history reveals striking disparities in urban development and access. While certain sections of the Bayou are adorned with green spaces and public art, reflecting cultural vitality, others have suffered under the weight of industrialization and environmental neglect.

The social justice implications of Buffalo Bayou's development are significant. The Bayou's history reflects the impact of evolving land use practices on marginalized communities. Inconsistent urban planning and recurrent flooding have disproportionately affected vulnerable populations along its banks, underlining the importance of inclusive urban development and spatial planning strategies.

Adjacent to Buffalo Bayou is Galena Park, an area contrasting sharply with the Bayou's recreational aspects due to its industrial heritage. As a hub of industrial activities, including refineries and warehouses, Galena Park has faced environmental justice challenges (See Fig. 5). The community, predominantly from lower-income backgrounds, contends with air and water pollution from nearby industries, highlighting significant health risks and environmental concerns (Bullard & Wright, 1986; Fang et al., 2023).

Yet, the narrative of Galena Park is not solely one of adversity; it also speaks of community resilience. Despite environmental challenges, residents have engaged in advocacy and activism, demanding accountability, and striving for a healthier living environment (Pulido, 2000). The examination of Buffalo Bayou and Galena Park unravels the complex layers of Houston's urban heritage, where economic development, environmental sustainability, and community resilience intersect (See Fig. 6). These neighborhoods, with their unique historical trajectories, epitomize Houston's broader themes of environmental justice and socio-cultural evolution. Their stories compel a reflection on the city's past and future,

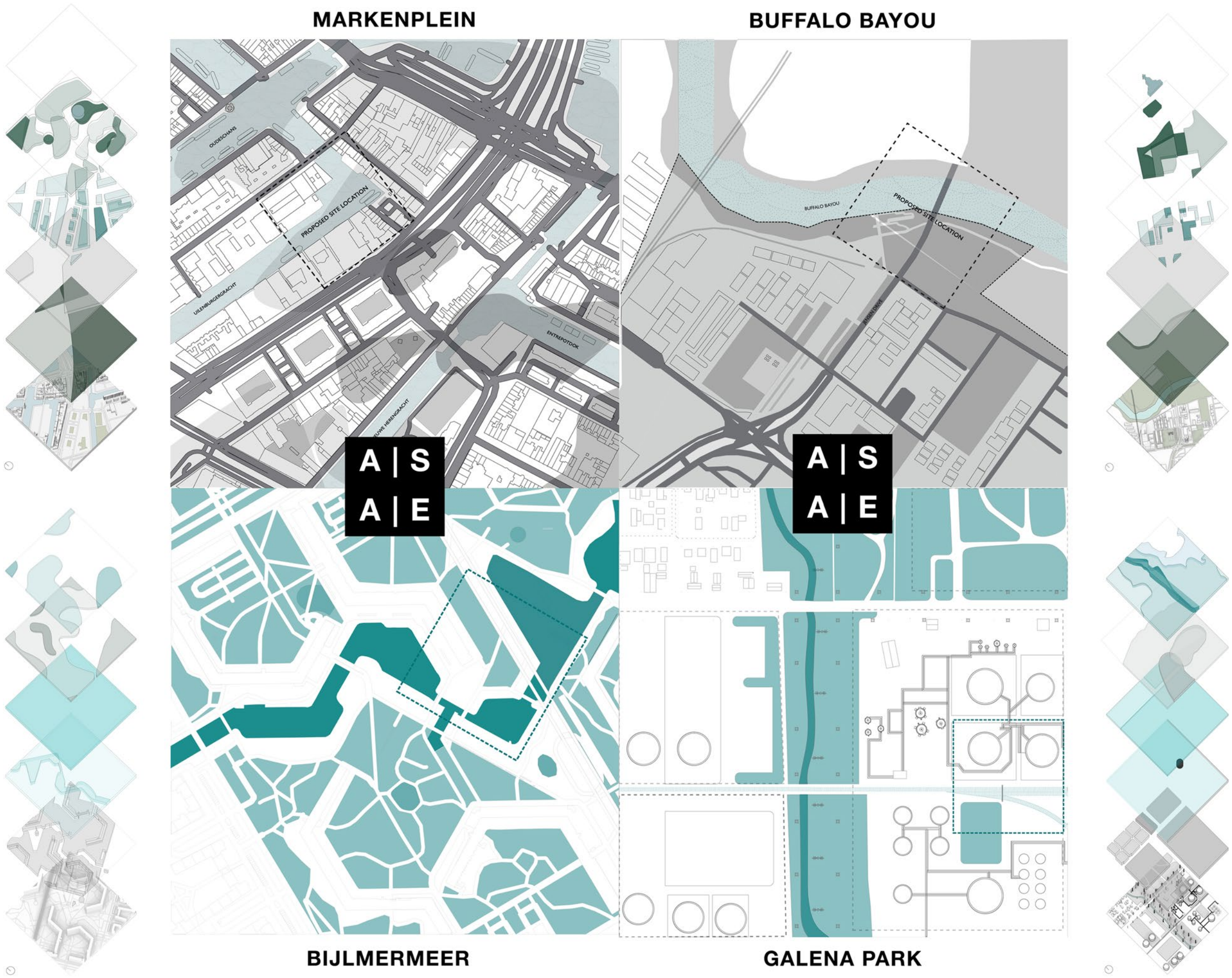

Fig. 5 Macro-maps of selected parcels in Houston and Amsterdam offer a two-dimensional perspective, complemented by isometric exploded maps that showcase a multilayered analysis from social and environmental justice viewpoints in both cities. For social justice, different elements such as religious buildings, immigration background, zoning, economic status, and crime rate have been analyzed through isometric exploded maps. For environmental justice, different features such as flood zones, heat island zones, air quality, pollution, and zoning have been analyzed through exploded isometric maps. Source: TTU HCOA Joint Studios (UCD+DFC) Led by Authors

emphasizing the need for urban planning that harmonizes economic aspirations with environmental stewardship and social justice.

6 Augmented reality in urban design: exploring socio-environmental dynamics in houston and amsterdam

In this study, we explored the multifaceted nature of urban design in Houston and Amsterdam, employing computational methodologies with a particular emphasis on Augmented Reality (AR) to delve into social and environmental justice issues. The research adopts an interdisciplinary approach, integrating computational urban design techniques to understand and represent complex urban narratives.

Houston's experience with urban sprawl, and its historical struggle with flooding, particularly in the bayou regions, exemplifies the socio-environmental repercussions of unchecked urban growth. These challenges underscore the necessity for ecologically sensitive and socially just urban planning (Bedient & Blackburn, 2007). Amsterdam's history as a water-centric city with its sophisticated water management systems presents a contrast yet complementary case to Houston. These systems, borne out of historical necessity, offer valuable insights into sustainable urban planning relevant in today's context of climate change.

The integration of AR in our study offers an immersive experience, allowing for a deeper engagement with the urban landscape (See Fig. 6). This technology enables

Fig. 6 An overview of the final installation result of TTU HCOA Joint Studios (UCD+DCF) led by authors, exhibited in Venice Architecture Biennale 2023, ECC Italy, Palazzo Mora, Venice. Photo by Federico Vespignani

users to traverse time and space, providing interactive narratives that illuminate the complex interplay between urban development, heritage, and socio-environmental justice.

The utilization of Augmented Reality (AR) in this study significantly enhances the understanding of urban heritage. AR merges the tangible aspects of built environments with the intangible qualities of historical narratives, offering an immersive exploration of urban history. Users navigating through Amsterdam or Houston via AR can experience a temporal journey, connecting with historical events, cultural transformations, and architectural evolutions. This integration of AR into urban studies enriches the appreciation and comprehension of cities' socio-environmental paths (See Fig. 6) (Bulkeley & Betsill, 2005).

In considering socio-environmental justice, this study demonstrates how urban heritage in Houston and Amsterdam is not merely a reflection of the past but also a driving force in addressing contemporary urban challenges. By utilizing AR, urban heritage becomes an engaging element in current urban discussions, bridging past and present to inspire future urban development (Mehan & Mostafavi, 2023b; Harvey, 2009).

The narratives of Amsterdam and Houston, rich in historical and socio-environmental lessons, offer invaluable insights for global urban planning. They underscore the critical relationship between preserving heritage and promoting justice, guiding the creation of cities that respect their history while proactively shaping an inclusive future (Soja, 2010; Swyngedouw, 2004; Holifield, Chakraborty, & Walker, 2018). The stories of these cities, as revealed through AR, provide a foundation for envisioning urban environments that honor their past while embracing the challenges and opportunities of the future.

This study highlights the dynamic nature of urban heritage as a critical factor in contemporary urban planning. It represents a dialogue encompassing past, present, and future, where urban heritage is not just a reflective account of history but a proactive participant in shaping current urban discourses. The application of AR/VR and computational design in this context is not just a methodological choice but a strategic tool to foster deeper connections between citizens and their urban environments, enhancing community engagement and participation in urban development processes.

7 Conclusions

This research critically examined the integration of computational technologies, particularly AR in urban planning, with a focus on the cities of Houston and Amsterdam. The study highlighted how computational tools can enhance the understanding of urban spaces and contribute to more effective and inclusive urban planning.

The research demonstrated that AR can be a valuable tool in visualizing the complex socio-environmental dynamics of cities like Houston, aiding in the development of strategies to address urban challenges. In Amsterdam, the integration of AR and computational design provided insights into how historical preservation can coexist with contemporary urban development, particularly in areas undergoing significant socio-economic changes.

Despite the promising findings, the study faced limitations, including the dependency on advanced technology and the need for specialized skills to implement AR in pedagogical practices. Additionally, the research was limited to two specific urban contexts, which may not be representative of all cities. The use of AR, VR, and XR technologies in urban design raises several ethical and accessibility challenges. Privacy concerns emerge due to the potential collection and use of personal data within urban environments. Additionally, these technologies may exacerbate the digital divide, as not everyone has access to the necessary hardware or internet connectivity. Ensuring inclusivity is crucial, requiring efforts to make these technologies accessible to people with disabilities and diverse backgrounds. Furthermore, the impact of AR, VR, and XR on cultural heritage is a significant consideration, encompassing concerns about the preservation and representation of cultural sites and traditions.

The comparative study between Houston and Amsterdam has revealed the versatility and adaptability of AR/XR technologies in urban planning. However, a more detailed analysis is necessary to demonstrate how these technologies were specifically tailored to address the unique challenges and opportunities present in each city.

In Houston, AR/XR technologies were employed to tackle issues related to urban sprawl, flooding, and community engagement in green space design. The AR applications developed for Houston focused on visualizing the impacts of urban expansion and potential flooding scenarios, allowing for more informed decision-making in urban development and disaster preparedness. Furthermore, AR was used to engage communities in the design of green spaces in underserved neighborhoods, providing a platform for residents to visualize and contribute to the planning process, thereby promoting inclusivity and environmental justice.

In contrast, Amsterdam's use of AR/XR technologies centered around historical preservation, climate change adaptation, and participatory urban redevelopment. XR applications in Amsterdam were designed to immerse users in the historical context of the city, enabling a deeper understanding and appreciation of its heritage. Additionally, AR was utilized to visualize the effects of sea-level rise in low-lying areas, aiding in the development of climate-resilient urban strategies. The involvement of residents in the redevelopment of historically marginalized areas through XR tools exemplified the potential for these technologies to foster community engagement and ensure that urban planning is reflective of diverse needs and perspectives.

The lessons learned from the application of AR/XR technologies in Houston and Amsterdam contribute significantly to the field of urban planning. In Houston, the importance of integrating AR/XR in disaster management and community-centric urban design was highlighted, while Amsterdam's experience underscored the value of these technologies in historical preservation and climate adaptation. These insights underscore the need for a context-specific approach in the deployment of AR/XR technologies, emphasizing the importance of understanding the unique characteristics and challenges of each urban environment.

The comparative analysis between Houston and Amsterdam demonstrates the dynamic and context-dependent nature of AR/XR technologies in urban planning. By showcasing how these technologies were adapted to meet the distinct needs of each city, the study provides valuable insights into their potential applications and the importance of a tailored approach in leveraging AR/XR for urban development. The lessons learned from each context contribute to a broader understanding of how AR/XR can be effectively integrated into diverse urban settings, offering a stronger foundation for the manuscript's claims, and advancing the discourse in the field of urban planning.

Addressing accessibility challenges is essential for the successful integration of AR, VR, and XR technologies in urban design. This includes making these technologies physically accessible to people with disabilities, such as those with mobility or visual impairments. Improving digital literacy among the population is also crucial to ensure that everyone can effectively use AR, VR, and XR technologies. Moreover, addressing the cost barriers that may prevent some individuals or communities from accessing these technologies is vital for promoting equitable urban design practices. By acknowledging and addressing these ethical and accessibility challenges, urban designers can create more inclusive and sustainable urban environments.

Future research could explore the scalability of AR applications in urban design across different cities and cultural contexts. Investigating the ethical implications of using AR in urban planning, particularly in terms of data privacy and security, is also crucial. Further exploration is needed to develop more accessible AR tools that can be easily integrated into existing urban planning frameworks and engage a broader range of community groups.

Furthermore, this research underscores the significance of computational urban design in reshaping urban planning. It advocates for a balanced approach that leverages technology to enhance urban planning while remaining attentive to the diverse needs and histories of urban communities. The findings from Houston and Amsterdam provide a framework for applying computational urban design in various urban settings, emphasizing its role in developing inclusive and just cities.

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Availability of data and materials
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