SUSTAINABLE URBAN REGENERATION IN MEDITERRANEAN CITIES: URBAN PLANNING PERSPECTIVES ON DIGITALIZATION AND ARTIFICIAL INTELLIGENCE

DOI: 10.26341/issn.2241-4010-2026-8a-2-L02167

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Abstract
Sustainable urban regeneration is a critical challenge for Mediterranean cities, where historic layers, compact built environments, and social complexity intersect with climate change pressures. In this context, digital transformation is reshaping urban planning and regeneration practices. Artificial Intelligence (AI), digital twins, Building Information Modelling (BIM), and Virtual Reality (VR) are increasingly employed in urban interventions, promising more resilient and adaptive futures while also raising questions of governance, ethics, and inclusiveness.

This paper explores the role of digital tools in advancing sustainable regeneration in Mediterranean cities. The methodology combines a critical review of emerging digital applications with case studies of innovative projects. Emphasis is placed on the contribution of digital tools to environmental assessment, quality-of-life indicators, and integrated planning, as well as on the risks of technological determinism and social inequality.

Findings indicate that digital technologies can optimize resource efficiency, support climate adaptation, and enhance participatory planning. For example, digital twins simulate the impact of adaptation strategies at neighborhood scale, while AI-driven models improve energy and mobility management. VR and AR tools enable citizens to visualize and co-design regeneration projects, strengthening public engagement. However, challenges persist: financial and technical demands often exceed municipal capacities, particularly in smaller Mediterranean cities, and ethical issues such as privacy and algorithmic bias threaten democratic governance. Importantly, digital divides risk excluding vulnerable populations from digitally driven regeneration processes.

The study concludes that sustainable urban regeneration requires balancing digital innovation with the cultural and environmental specificities of Mediterranean urbanism. Compact urban forms, historic centers, and strong community ties must guide the adaptation of digital tools. Interdisciplinary approaches that link urban design, digital technology, and social sciences are essential to ensure that the digital transition enhances, rather than undermines, sustainability, resilience, and equity.

Key words: *Urban regeneration, mediterranean cities, sustainable development, artificial intelligence, digital twins, virtual reality, smart cities*

INTRODUCTION

Mediterranean cities constitute complex urban ecosystems shaped by historical continuity, dense spatial configurations, and strong socio-cultural identities. These characteristics, while representing significant cultural capital, simultaneously intensify contemporary urban challenges related to environmental sustainability, climate resilience, and social cohesion (UN-Habitat, 2020). In recent decades, the need for sustainable urban regeneration has emerged as a central priority for Mediterranean urban policy and planning, particularly as cities confront escalating climate pressures, demographic transformations, and socio-economic inequalities. Sustainable urban regeneration is increasingly conceptualized as a multidimensional process integrating environmental, social, economic, and cultural dimensions of urban development (Dixon et al., 2008; Kalemis, 2024).

Mediterranean urban environments are particularly vulnerable to climate-related risks, including heat island effects, water scarcity, coastal degradation, and infrastructure stress caused by extreme weather events. At the same time, the preservation of historic urban fabrics and cultural heritage presents additional constraints for regeneration strategies, requiring interventions that balance conservation with innovation. Urban sustainability in such contexts extends beyond environmental performance to encompass social inclusiveness, democratic participation, and cultural continuity. As Amin (2006) argues, sustainable cities must promote equitable urban citizenship and social interaction while maintaining spatial and cultural diversity. Similarly, ecological urbanism approaches highlight the need for integrated planning strategies that align environmental adaptation with urban design innovation and socio-cultural values (European Commission, 2019).

Within this evolving planning landscape, digital transformation has emerged as a significant driver reshaping urban regeneration practices. Advances in digital technologies are enabling new forms of urban analysis, modelling, and participatory planning, transforming traditional planning methodologies into data-driven and simulation-based decision-making processes. Technologies such as Building Information Modelling (BIM), digital twins, artificial intelligence (AI), and immersive visualization environments, including Virtual Reality (VR) and Augmented Reality (AR), are increasingly employed to support sustainable urban interventions. These digital tools facilitate integrated urban management by enabling real-time environmental monitoring, predictive modelling, and improved coordination between stakeholders and governance levels.

BIM technologies, for instance, support lifecycle sustainability assessment and resource optimization across built environment projects, enhancing planning accuracy and cost efficiency (Kamari et al., 2020). Digital twins extend these capabilities by allowing real-time simulation of urban systems, supporting climate adaptation planning, infrastructure resilience, and energy optimization strategies (Post et al., 2017; Boyes et al., 2018). Artificial intelligence further strengthens urban resilience through predictive analytics, automated decision support, and smart infrastructure management. However, algorithmic governance also introduces ethical challenges concerning transparency, accountability, and social equity, raising concerns about data privacy, algorithmic bias, and democratic legitimacy in urban decision-making processes (Sharma, 2025).

Simultaneously, immersive digital environments such as VR and AR are transforming participatory urban planning by enabling citizens to visualize, experience, and co-design regeneration proposals. These technologies enhance public engagement and improve communication between planners, policymakers, and local communities, contributing to more inclusive and socially sustainable regeneration processes (Jamei et al., 2017; Nikolić & Whyte, 2021). Moreover, the emergence of human-centric digital design frameworks emphasizes the

importance of aligning technological innovation with societal needs and ethical governance principles, reinforcing the concept of digital humanism in urban planning (Najafi et al., 2025).

Against this background, this study aims to explore the role of digital technologies in advancing sustainable urban regeneration within Mediterranean cities. The research investigates how AI, BIM, digital twins, and immersive visualization tools contribute to environmental sustainability, urban resilience, and participatory governance while addressing the socio-cultural specificities of Mediterranean urban contexts. Particular attention is given to the opportunities and risks associated with digital urban transformation, including technological determinism, digital divides, and governance challenges.

Methodologically, the study adopts a qualitative research approach combining a critical literature review with the analysis of selected case studies from Mediterranean urban environments. The literature review examines theoretical frameworks and empirical research concerning digital urbanism, sustainability planning, and socio-technical governance. Case studies are used to illustrate practical applications of digital tools in urban regeneration projects, providing insights into their effectiveness, limitations, and transferability across Mediterranean cities. Through this combined analytical framework, the study seeks to contribute to the ongoing discourse on sustainable urban regeneration by proposing integrated and human-centered digital planning strategies tailored to Mediterranean urban realities.

MEDITERRANEAN URBANISM: ENVIRONMENTAL AND SOCIO-SPATIAL CHALLENGES

Mediterranean urbanism is defined by a distinctive convergence of historical continuity, compact morphology, climatic exposure, and deeply embedded socio-cultural practices. Cities across the Mediterranean basin have evolved through layered historical processes, producing dense urban fabrics in which contemporary life coexists with archaeological strata, vernacular building typologies, and enduring public space traditions. This morphological density has long supported walkability, mixed uses, and intense social interaction. Yet under conditions of climate change, socio-economic restructuring, and digital transition, the same structural characteristics now generate complex environmental and governance challenges.

Unlike Northern European or globally standardized metropolitan models, Mediterranean cities are characterized by narrow street canyons, deep urban blocks, high building coverage ratios, and semi-private courtyard systems. Historically, such compactness provided climatic advantages, such as shading, wind protection, and passive cooling, contributing to energy-efficient vernacular environments. However, rising temperatures and prolonged heatwaves have altered this balance. Spatial configurations that once mitigated climatic extremes increasingly intensify urban heat island (UHI) effects, restrict air circulation, and exacerbate heat accumulation.

Empirical research on Mediterranean urban morphology confirms that street canyon geometry plays a decisive role in thermal performance. High height-to-width (H/W) ratios are associated with reduced air exchange and increased thermal stress during heatwave events (Tsirigoti & Tsikaloudaki, 2018). More recent studies demonstrate that canyon orientation, surface materials, albedo values, and vegetative cover significantly influence solar exposure and nocturnal heat retention cycles (Tsirigoti, 2025b). These findings suggest that Mediterranean urban density, once a climate-adaptive strategy, now contributes to overheating, with direct implications for energy consumption, livability, and public health.

The environmental challenges of Mediterranean cities extend beyond heat stress. Dense block structures limit permeable surfaces and reduce opportunities for vegetation and ecological connectivity. Fragmented open spaces constrain the implementation of large-scale nature-based solutions, while heritage preservation requirements restrict extensive

infrastructural redesign (IPCC, 2022). As Mostafavi and Doherty (2016) argue within ecological urbanism discourse, sustainable regeneration in such contexts must integrate environmental systems with cultural landscapes through adaptive, multi-scalar approaches rather than standardized interventions.

A defining yet often overlooked element of Mediterranean morphology is the inner courtyard. Present in the majority of multi-storey urban blocks, courtyards function as semi-private micro-urban ecosystems with substantial environmental and social potential. Recent research identifies inner courtyards as microclimatic sinks capable of lowering local air temperatures, enhancing ventilation, and supporting small-scale cooling strategies (Tsirigoti, 2025a). Vegetative integration, permeable paving, reflective surfaces, and vertical greening systems can significantly improve courtyard thermal performance. Moreover, simulation studies demonstrate that block-scale renovation scenarios, combining façade retrofits, roof interventions, and courtyard upgrading, reduce energy demand and enhance comfort conditions (Tsirigoti, Zenginis & Bikas, 2021; 2022).

Courtyards, however, are not merely environmental devices. They hold strong socio-cultural significance as communal gathering spaces embedded in everyday Mediterranean life. Historically serving as semi-public nodes of domestic and social interaction, they contribute to collective identity and place attachment. Their regeneration therefore intersects environmental resilience with cultural sustainability, a concept extending beyond heritage preservation to include intangible practices, social networks, and lived urban memory (Crang, 2015; Travis, 2017).

Environmental vulnerability in Mediterranean cities is closely intertwined with socio-economic inequality. Access to thermally comfortable public space remains unevenly distributed, with marginalized populations often disproportionately exposed to heat stress. Tourism-driven development, speculative housing markets, and demographic change further intensify spatial polarization in historic centers. As Amin (2006) argues, the quality of the "good city" depends not only on physical performance but on equitable access to urban resources and meaningful civic participation. Colantonio and Dixon (2011) similarly emphasize social sustainability as a central dimension of urban regeneration, highlighting participation, cohesion, and place-based identity as critical factors in long-term transformation.

In this context, sustainable urban regeneration in Mediterranean cities cannot be reduced to physical upgrading or environmental optimization. It must reconcile environmental adaptation, social justice, and cultural continuity. The complexity of Mediterranean urban fabrics, morphologically dense, climatically vulnerable, socially layered, requires integrated planning approaches that combine microclimatic knowledge, morphological sensitivity, and participatory governance.

At the same time, governance structures often remain fragmented, with limited integration between environmental monitoring systems, spatial planning instruments, and digital data infrastructures. The adoption of digital tools, ranging from environmental sensing to immersive participation platforms, introduces both opportunities and risks. While digital transformation offers enhanced modelling capacity and real-time climate monitoring, digital divides may reproduce socio-spatial inequalities if participation mechanisms are not inclusively designed (Ridell, 2008).

Recent regeneration initiatives illustrate these tensions. Barcelona's Superblocks program demonstrates how public space reallocation, mobility restructuring, and environmental monitoring can reinforce neighborhood-scale social life while mitigating heat and pollution. In contrast, large-scale redevelopment projects such as Athens' Ellinikon reveal the complexity of balancing investment-driven regeneration with inclusive governance and metropolitan integration, reducing the effects of urban sprawl in the waterfront location

(Theodora & Spanogianni, 2022; 2026). Similarly, cities such as Naples and Málaga must reconcile tourism-led growth with environmental resilience and cultural authenticity.

These cases underline a central insight: Mediterranean urbanism constitutes a critical testing ground for sustainable regeneration models that must operate within historically layered, climate-sensitive, and socially embedded contexts. Sustainability in this region cannot be imported as a generic smart city formula. It must be culturally grounded, climatically responsive, and spatially adaptive.

The environmental and socio-spatial challenges outlined above establish the foundation for examining how emerging digital technologies (BIM, Digital Twins, AI-driven analytics, and immersive systems) can operationalize microclimatic intelligence, support adaptive design, and foster inclusive governance. Digital transformation, when aligned with the morphological and cultural specificity of Mediterranean urbanism, becomes not a technocratic overlay but a strategic mediator between climate resilience, spatial form, and social sustainability.

DIGITAL TRANSFORMATION AND SMART URBAN REGENERATION

The growing complexity of urban challenges has accelerated the adoption of digital technologies in urban planning and regeneration processes. Over the past two decades, the concept of the "smart city" has evolved from a technology-driven model focused on efficiency and automation toward a broader paradigm of digital urbanism that emphasizes integration, adaptability, and human-centered design. This shift reflects increasing recognition that technological solutions alone cannot address urban sustainability without consideration of social, cultural, and governance dimensions.

Digital urbanism encompasses a range of interconnected technologies that support data-driven decision-making, system integration, and participatory planning. Among these, Building Information Modelling (BIM) has emerged as a foundational tool for sustainable urban development. BIM enables the creation of detailed digital representations of buildings and infrastructure, supporting lifecycle assessment, resource optimization, and coordinated planning across disciplines. In the context of urban regeneration, BIM facilitates sustainability-oriented design decisions by integrating environmental performance, cost analysis, and maintenance considerations throughout the project lifecycle (Kamari et al., 2020).

Building upon BIM, digital twins represent a significant advancement in urban modelling and simulation. Digital twins are dynamic, data-driven replicas of physical urban systems that enable real-time monitoring, scenario testing, and predictive analysis. At the urban scale, digital twins support energy modelling, climate adaptation strategies, and infrastructure resilience by simulating the impacts of policy interventions and environmental changes. When combined with Internet of Things (IoT) infrastructures, digital twins enable continuous feedback loops between the physical city and its digital counterpart, enhancing responsiveness and adaptive capacity (Batty, 2018).

The integration of BIM, Geographic Information Systems (GIS), and digital twins further enhances spatial holism in urban planning. GIS provides the geospatial framework necessary to contextualize building-level data within broader urban systems, enabling multi-scalar analysis of land use, mobility, environmental conditions, and socio-economic patterns. This integrated digital ecosystem supports more informed and coordinated regeneration strategies, particularly in dense and historically complex Mediterranean urban environments.

Artificial intelligence (AI) plays a complementary role by enabling advanced analytics, pattern recognition, and predictive modelling across urban systems. AI-driven tools are increasingly applied to optimize traffic flows, energy consumption, waste management, and

climate risk assessment. In regeneration contexts, AI supports scenario evaluation and decision-making under uncertainty, enhancing urban resilience and operational efficiency. However, the growing reliance on algorithmic systems also raises critical concerns regarding transparency, accountability, and social equity (Kalemis, 2025c).

The risk of technological determinism, where technological capabilities drive planning decisions without adequate social or ethical scrutiny, remains a central challenge in digital urban regeneration. Algorithmic governance may reinforce existing inequalities if data biases, unequal access to digital tools, and opaque decision-making processes are not adequately addressed. Human-centric digitalization frameworks argue for the alignment of technological innovation with democratic values, participatory governance, and social inclusion (Kalemis, 2025c). In this perspective, digital tools should function as enablers of collective intelligence rather than substitutes for human judgment and civic deliberation.

In Mediterranean cities, where social interaction, cultural identity, and public space play a fundamental role in urban life, the human-centric approach to digital transformation is particularly critical. Digital technologies must be adapted to local contexts, supporting inclusive participation, cultural sustainability, and context-sensitive regeneration rather than imposing standardized smart city models. By integrating BIM, digital twins, AI, and participatory digital platforms within a coherent socio-technical framework, digital urbanism offers significant potential to enhance sustainable urban regeneration while respecting the unique characteristics of Mediterranean urban environments.

ARTIFICIAL INTELLIGENCE AND URBAN RESILIENCE

The increasing frequency and intensity of environmental, social, and infrastructural disruptions have elevated urban resilience as a central objective of contemporary planning and regeneration strategies. Urban resilience refers to the capacity of cities to anticipate, absorb, adapt to, and recover from environmental shocks, socio-economic crises, and technological disruptions while maintaining essential urban functions and social stability. Within this framework, artificial intelligence (AI) is emerging as a transformative tool capable of enhancing adaptive urban governance, predictive planning, and integrated infrastructure management.

AI-driven urban systems rely on large-scale data collection, machine learning algorithms, and predictive analytics to support decision-making processes across multiple urban sectors. In climate-sensitive Mediterranean cities, where environmental vulnerability intersects with dense urban morphology and socio-cultural complexity, AI offers substantial opportunities to strengthen adaptive planning. Through the analysis of environmental data, mobility patterns, and energy consumption, AI systems enable early warning mechanisms, real-time monitoring, and optimization of urban services. These capabilities support proactive rather than reactive urban management, enhancing resilience against climate-related hazards such as heatwaves, flooding, and air pollution.

One of the most significant applications of AI in urban resilience relates to environmental monitoring and climate adaptation. Machine learning algorithms can process large environmental datasets derived from satellite imagery, sensor networks, and digital twins to identify vulnerability hotspots and predict climate risks. AI-driven climate modelling supports urban heat mitigation strategies, flood risk mapping, and optimization of green infrastructure planning (European Commission, 2023). Such data-driven approaches allow urban planners to simulate alternative regeneration scenarios and evaluate their environmental and social impacts before implementation. Beyond environmental applications, AI also contributes to infrastructural and mobility resilience. Intelligent transport systems utilize AI algorithms to manage traffic flows, reduce congestion, and optimize public transportation

networks. These systems improve urban accessibility and reduce greenhouse gas emissions, contributing to both environmental sustainability and economic efficiency. Additionally, AI supports predictive maintenance of urban infrastructure by identifying structural vulnerabilities and forecasting maintenance needs, reducing long-term operational costs and enhancing infrastructure reliability (Kalemis, 2025b).

Despite these advantages, the integration of AI into urban governance introduces significant ethical, social, and political challenges. Algorithmic decision-making processes often operate through opaque computational models, raising concerns regarding transparency, accountability, and democratic legitimacy. As Werthner et al. (2024) emphasize, algorithmic governance risks reinforcing existing social inequalities if data biases and digital exclusion are not adequately addressed. Urban data infrastructures frequently reflect existing socio-economic disparities, potentially marginalizing vulnerable communities if AI systems prioritize efficiency over equity.

In response to these concerns, human-centric AI frameworks advocate for participatory governance, ethical algorithm design, and inclusive data practices. Digital humanism perspectives emphasize that AI systems should support collaborative decision-making rather than replace human agency. In Mediterranean cities, where community identity and social interaction are fundamental components of urban life, such human-centered approaches are particularly relevant. Urban resilience therefore depends not only on technological capacity but also on governance models that integrate citizen participation and cultural sensitivity.

The application of AI and related digital technologies in Mediterranean urban regeneration can be illustrated through emerging case studies. In Barcelona, the Superblocks (Superilles) initiative integrates digital monitoring systems and data analytics to evaluate environmental and social impacts of traffic reduction strategies (Frago & Morcuende González, 2024). Urban data platforms and sensor networks support real-time monitoring of air quality, noise levels, and mobility patterns, enabling adaptive policy adjustments and evidence-based planning. AI-supported urban analytics contribute to the optimization of pedestrian networks, public space allocation, and climate mitigation strategies, reinforcing Barcelona's transition toward human-centered urban resilience.

Athens provides a contrasting yet equally instructive example through the large-scale regeneration project at the Ellinikon Metropolitan Park development. Digital modelling tools, including BIM and digital twin technologies, have been employed to support environmental simulation, infrastructure planning, and energy optimization within the redevelopment process. AI-driven analytics are increasingly explored for mobility management, energy efficiency modelling, and climate adaptation strategies within the broader metropolitan region (The Ellinikon, 2026). However, the project also illustrates governance challenges associated with large-scale digital urban projects, including questions of public participation, social inclusiveness, and equitable access to regenerated urban spaces (Theodoropoulou, 2025).

In Naples, digital mapping and data analytics are being used to support heritage preservation and tourism management. AI-assisted cultural heritage monitoring allows planners to track visitor flows, structural stress on historic sites, and environmental impacts of tourism, supporting sustainable heritage management strategies (Aria et al., 2023; Sommella & D'Alessandro, 2021). Similarly, Málaga has invested in smart urban platforms that integrate energy monitoring, public service optimization, and environmental data analysis (Barke & Newton, 1995). These initiatives demonstrate how AI-driven urban management can support both economic development and environmental sustainability, particularly in tourism-dependent Mediterranean economies.

The comparative analysis of these case studies highlights the importance of integrating AI within broader socio-technical planning frameworks. Successful AI-based urban resilience strategies require the coordination of digital infrastructure, governance mechanisms, and

community participation. Mediterranean cities demonstrate that technological innovation alone cannot ensure sustainable regeneration without consideration of cultural identity, social equity, and participatory governance structures.

Consequently, AI should be conceptualized not merely as a technological instrument but as a component of integrated urban knowledge systems. By combining AI with digital twins, BIM, and participatory digital platforms, urban planners can develop adaptive, evidence-based regeneration strategies capable of addressing complex urban challenges. In Mediterranean contexts, where environmental vulnerability intersects with strong cultural and social identities, AI-driven urban resilience must prioritize human-centered innovation, ensuring that digital transformation enhances both environmental sustainability and urban inclusiveness.

IMMERSIVE TECHNOLOGIES (VR/AR) AND PARTICIPATORY URBAN PLANNING

While artificial intelligence and digital twins enhance predictive capacity and infrastructural optimization, immersive technologies such as Virtual Reality (VR) and Augmented Reality (AR) expand the social and participatory dimensions of digital urban regeneration. In the context of Mediterranean cities, where public space, social interaction, and collective identity constitute core elements of urban life, immersive digital environments provide significant opportunities to strengthen democratic engagement and co-creative planning practices (Kalemis, 2025a).

Participatory planning has long been recognized as essential for socially sustainable regeneration, particularly in culturally dense and historically layered urban environments (Amin, 2006; Colantonio & Dixon, 2011). However, conventional participatory mechanisms, such as public hearings, static masterplans, and two-dimensional representations, often limit citizens' ability to fully comprehend spatial transformations or evaluate alternative design scenarios. Immersive technologies address this limitation by enabling experiential visualization of proposed interventions, allowing users to "inhabit" projected urban futures before their physical realization.

Virtual Reality applications allow planners, stakeholders, and residents to explore regeneration scenarios in three-dimensional, interactive environments. Such tools improve spatial understanding, enhance transparency in planning processes, and facilitate informed public deliberation. Jamei et al. (2017) demonstrate that VR-based visualization significantly improves citizens' comprehension of complex urban proposals, particularly in dense environments where spatial impacts are difficult to interpret through conventional drawings. Similarly, Nikolić and Whyte (2021) argue that immersive modelling environments foster collaborative learning and shared decision-making among multidisciplinary actors.

In Mediterranean cities, where urban regeneration frequently involves interventions in historic centers, waterfronts, and culturally sensitive public spaces, immersive technologies can function as mediating platforms between conservation and innovation. For example, VR simulations can evaluate the visual impact of pedestrianization schemes, green infrastructure integration, or façade restoration projects within historic urban fabrics. By enabling stakeholders to compare alternative scenarios, immersive tools reduce conflict, enhance negotiation processes, and support culturally sensitive design outcomes.

Augmented Reality further extends participatory capabilities by overlaying digital information onto existing urban spaces. Through AR interfaces, citizens can visualize proposed interventions in situ, using mobile devices or wearable technologies. This real-time contextualization supports site-specific engagement and strengthens the relationship between digital representation and lived urban experience. AR tools are particularly relevant in

tourism-intensive Mediterranean cities such as Naples and Málaga, where heritage interpretation, visitor management, and public space enhancement must be carefully balanced.

Barcelona's Superblocks initiative provides an illustrative example of how immersive and digital visualization tools can support participatory urban transformation. The reallocation of street space from vehicular traffic to pedestrian and community uses required extensive public communication and scenario testing (López et al., 2020). Digital simulations and interactive visualizations facilitated public understanding of traffic redistribution, environmental benefits, and public space redesign, strengthening citizen acceptance and adaptive governance processes. Immersive visualization thus complemented data-driven AI analytics and environmental monitoring systems, reinforcing an integrated digital ecosystem (Anguelovski et al., 2023).

In Athens, large-scale regeneration initiatives such as the Ellinikon Metropolitan Park redevelopment highlight both the potential and limitations of immersive planning tools. While digital modelling and visualization technologies have been employed to present masterplan proposals and environmental simulations, questions remain regarding the depth of participatory integration and inclusiveness. Immersive technologies, when embedded within transparent governance frameworks, can enhance civic dialogue; however, when used primarily as promotional visualization tools, they risk reinforcing top-down planning approaches. This distinction underscores the importance of aligning immersive technologies with democratic planning principles.

Beyond visualization, immersive environments increasingly intersect with emerging concepts such as the metaverse and hybrid digital-physical public spaces. These developments open new possibilities for civic interaction, urban experimentation, and digital co-production of space. Mystakidis (2022) conceptualizes immersive virtual environments as platforms for collaborative learning and social interaction, suggesting that metaverse-like systems may support new forms of urban engagement. At the policy level, the European Commission (2023) emphasizes both the opportunities and regulatory challenges associated with virtual worlds, particularly concerning data governance, digital rights, and social inclusion.

Nevertheless, the expansion of immersive planning technologies also raises critical concerns. Digital participation risks excluding populations with limited access to digital infrastructure or technological literacy, potentially reinforcing socio-economic divides. Moreover, immersive simulations may create persuasive visual narratives that influence public perception without fully disclosing underlying assumptions or data constraints. As with AI-driven analytics, immersive technologies must therefore operate within transparent, accountable, and human-centered governance frameworks.

In Mediterranean urban contexts, where social cohesion and cultural identity are foundational elements of urban resilience, immersive technologies should be conceptualized as facilitators of collective imagination rather than deterministic planning instruments. When integrated with AI analytics, BIM systems, and digital twins, VR and AR platforms can bridge the gap between technical expertise and community knowledge. This integration supports not only environmentally optimized regeneration strategies but also socially embedded and culturally responsive urban futures.

Ultimately, immersive technologies expand the scope of digital urbanism by incorporating experiential and participatory dimensions into sustainable urban regeneration. In Mediterranean cities, their effective deployment depends on balancing technological sophistication with inclusiveness, cultural sensitivity, and democratic accountability. By fostering informed citizen engagement and shared spatial understanding, immersive digital tools contribute to a more resilient, adaptive, and socially grounded model of urban transformation.

COMPARATIVE DISCUSSION AND INTEGRATED FRAMEWORK PROPOSAL

The comparative analysis of Mediterranean urban regeneration initiatives demonstrates that sustainable transformation cannot be achieved through isolated technological interventions or fragmented planning strategies. Instead, resilience and sustainability emerge from the integration of environmental adaptation, socio-cultural continuity, participatory governance, and digital innovation within a coherent socio-technical framework.

The cases of Barcelona, Athens, Naples, and Málaga reveal differentiated trajectories of digital urbanism. Barcelona's Superblocks initiative illustrates a relatively mature integration of data-driven governance, environmental monitoring, and participatory communication tools. Here, AI-supported analytics, mobility simulations, and digital visualization platforms operate within a broader human-scale urban design strategy. Digital tools are not ends in themselves but instruments reinforcing pedestrianization, environmental quality, and neighborhood-level social interaction.

In contrast, the Athens Ellinikon redevelopment project reflects the complexities of large-scale metropolitan regeneration in economically constrained contexts. While advanced BIM systems, environmental simulations, and digital modelling technologies support design and infrastructure optimization, tensions remain regarding inclusiveness, social accessibility, and participatory depth. The case highlights the risk of digital sophistication coexisting with limited democratic integration.

Naples and Málaga demonstrate hybrid models in which smart urban platforms, tourism management systems, and environmental monitoring tools are progressively integrated into heritage-sensitive urban fabrics. These examples underline the importance of aligning digital innovation with local socio-economic structures and cultural identity.

Across these cases, three recurring patterns emerge:

1. *Digital Integration Enhances Environmental Performance.* The combination of BIM, GIS, digital twins, and AI analytics improves lifecycle assessment, climate modelling, infrastructure resilience, and mobility optimization.
2. *Participatory Digital Tools Strengthen Social Legitimacy*. VR/AR visualization and interactive platforms enhance transparency and stakeholder.
3. *Governance Structures Determine Outcomes*. Technological capacity alone does not guarantee equitable regeneration. Institutional design and regulatory frameworks shape whether digital transformation fosters inclusiveness or reinforces.

Table 1. Integrated Mediterranean Urban Regeneration Comparative Matrix

City	Environmental Stress & Climate Strategy	Digital Integration (BIM–DT–AI–VR)	Social Equity & Participation	Governance & Ethical Digitalization
Naples	High density; waste & tourism pressure; adaptive reuse strategies.	Limited systematic BIM/DT deployment; sector-specific analytics.	Citizen perception studies in tourism sustainability; socio-economic inequality visible.	Municipal-regional coordination; digital governance less institutionalized.
Málaga	Tourism-driven growth; energy sustainability focus.	Energy modelling and sectoral digital tools; moderate smart systems.	Consultation within tourism & mobility policy; moderate inclusion mechanisms.	Municipal planning-driven governance; limited AI-driven regulation.
Barcelona	Heat islands; traffic congestion. Superblocks reduce car	Advanced use of data analytics; digital mobility modelling;	Strong participatory urbanism tradition; equity debates	High municipal capacity; growing emphasis on

	dominance and enhance microclimate & air quality.	emerging digital twin logic.	around redistribution of space.	transparency and public accountability.
Athens	Heat stress; coastal sprawl; large-scale regeneration (Ellinikon, Double Regeneration).	BIM in project-level planning; limited urban-scale digital twins; AI potential emerging.	Participation fragmented; risk of gentrification in flagship developments.	Mixed state–private governance; limited formal AI accountability framework.

Toward an Integrated Mediterranean Digital Regeneration Framework

Building on the comparative analysis of Mediterranean regeneration initiatives, this study proposes an Integrated Mediterranean Digital Regeneration Framework (IMDRF) structured as a coherent socio-technical system rather than a collection of discrete technological tools. The framework conceptualizes digital transformation as an embedded, multi-layered architecture that aligns environmental intelligence, spatial coordination, participatory engagement, and ethical governance within the specific morphological and cultural conditions of Mediterranean urbanism.

At its foundation lies an environmental intelligence layer, designed to enhance adaptive capacity in climate-vulnerable urban contexts. Mediterranean cities, characterized by dense fabrics and increasing heat stress, require real-time and predictive environmental knowledge systems. This layer integrates AI-driven climate modelling, urban digital twins capable of dynamic simulation, and distributed sensor networks monitoring temperature, humidity, air quality, and energy performance. Through predictive analytics and scenario modelling, municipalities can evaluate heat mitigation strategies, optimize water management systems, and assess energy performance across multiple temporal scales. Rather than reacting to climatic events, planning institutions are equipped to anticipate and simulate environmental impacts before implementing physical interventions. In this sense, environmental intelligence transforms sustainability from a reactive objective into a continuous adaptive process.

The second pillar, the spatial integration layer, ensures coherence across scales of intervention. Mediterranean regeneration often unfolds simultaneously at building, block, district, and metropolitan levels. Fragmented planning tools frequently undermine systemic sustainability by isolating architectural retrofits from broader territorial strategies. The integration of Building Information Modelling (BIM) for lifecycle management, Geographic Information Systems (GIS) for territorial analysis, and urban-scale digital twins for scenario coordination enables multi-scalar alignment. BIM contributes detailed material, structural, and energy performance data at the building level, while GIS situates these interventions within broader environmental and socio-spatial patterns. Urban digital twins synthesize these datasets into interoperable platforms capable of modelling cumulative impacts. This spatial integration layer thus bridges the gap between microclimatic retrofitting, such as courtyard upgrading or façade interventions, and metropolitan sustainability objectives, including mobility restructuring, green infrastructure networks, and carbon neutrality targets.

Complementing environmental and spatial intelligence, the participatory immersive layer embeds civic engagement within digital regeneration processes. Mediterranean cities possess strong traditions of public life and collective spatial identity; regeneration strategies that neglect this social dimension risk eroding legitimacy and cultural continuity. Through VR and AR platforms, interactive digital consultations, and scenario-based co-design tools, citizens can experience proposed transformations in immersive environments prior to implementation. Such tools enhance transparency, facilitate informed deliberation, and reduce conflict by allowing stakeholders to compare alternative design scenarios in real time. Importantly, immersive participation should not function as a merely representational device but as a deliberative infrastructure enabling co-production of urban futures. When integrated with

environmental modelling systems, immersive platforms allow communities to visualize the climatic and spatial consequences of planning decisions, strengthening both accountability and collective ownership.

The fourth pillar, the governance and ethical layer, anchors the technological architecture within democratic principles. The expansion of AI-driven analytics, predictive modelling, and algorithmic optimization in urban management introduces critical questions concerning transparency, accountability, and data justice. This layer incorporates mechanisms for explainable AI governance, algorithmic auditing, data protection safeguards, and digital inclusion policies. In Mediterranean contexts where socio-economic inequalities and fragmented institutional responsibilities often shape regeneration outcomes, ethical governance becomes indispensable. Technological systems must augment human decision-making without obscuring political responsibility. Clear accountability structures, open data frameworks, and inclusive access to digital participation tools ensure that innovation reinforces democratic urbanism rather than technocratic centralization (Kalemis, 2025c).

Taken together, these four pillars form an integrated ecosystem rather than a hierarchical sequence. Environmental intelligence informs spatial planning; spatial integration supports immersive participation; participatory inputs shape governance priorities; and ethical oversight regulates the deployment of artificial intelligence and digital infrastructures. The framework thus operates as a dynamic feedback system in which data, design, and deliberation are continuously interlinked.

Conceptually, the IMDRF advances beyond conventional smart city paradigms in three principal ways. First, it embeds the socio-cultural specificity of Mediterranean urbanism within digital transformation processes, recognizing that dense morphologies, courtyard systems, and public space traditions require context-sensitive technological mediation. Second, it rejects technological determinism in favor of digital–human symbiosis, positioning AI and modelling systems as collaborative instruments within participatory governance structures. Third, it reframes resilience as a socio-technical construct, emerging from the interaction between environmental modelling, spatial design, civic engagement, and ethical regulation.

Rather than interpreting digital transformation as a purely infrastructural upgrade, the framework conceptualizes it as an adaptive knowledge ecosystem. Within this ecosystem, environmental data, spatial intelligence, cultural memory, and civic participation are continuously mediated through interoperable digital platforms. Sustainable regeneration in Mediterranean cities, therefore, is not achieved through isolated smart interventions but through the orchestration of integrated digital capacities aligned with climatic realities, morphological constraints, and democratic values.

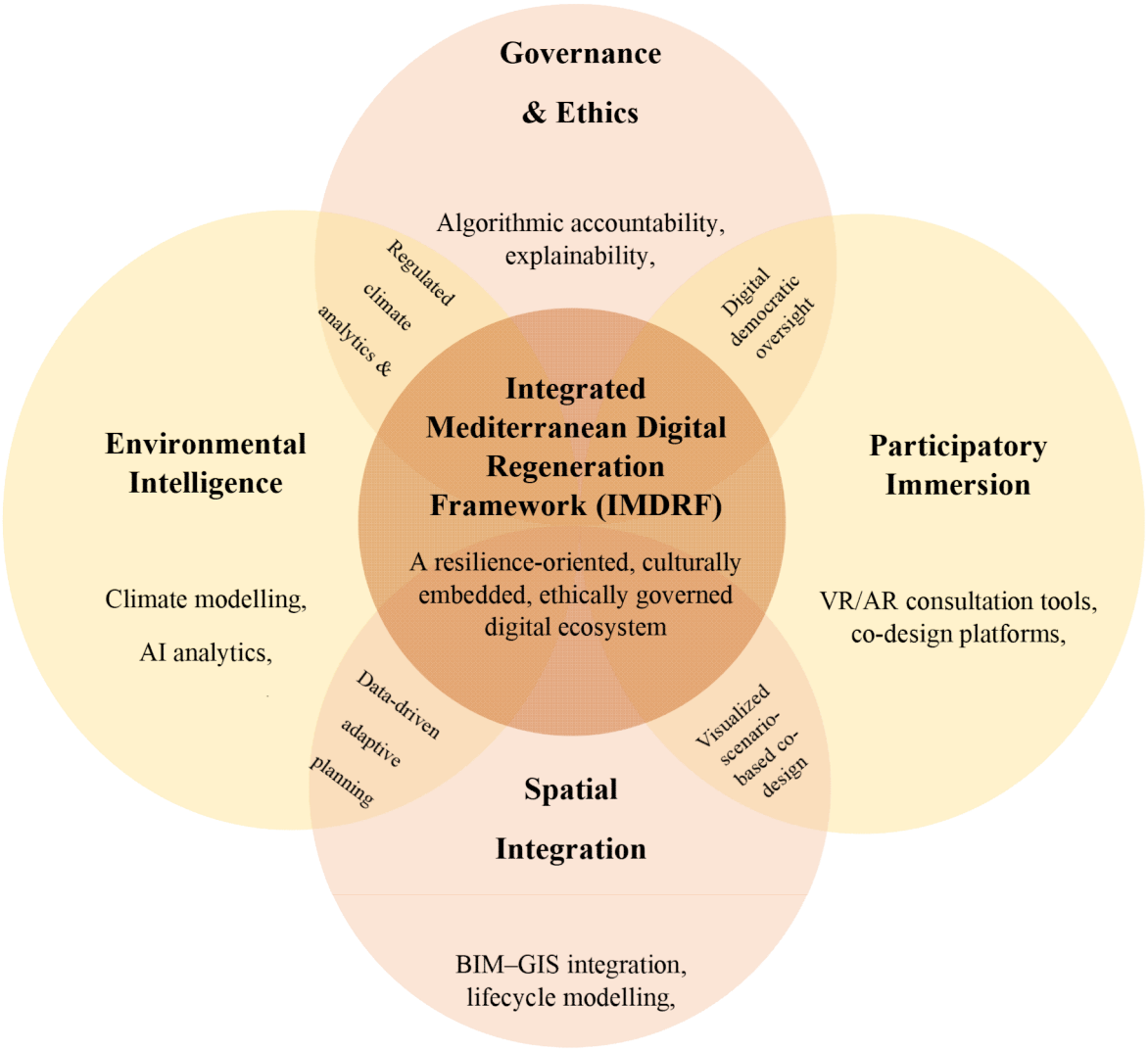
Governance, Ethics and Human-Centered Digital Urbanism

As digital technologies become structurally embedded within urban governance systems, questions of power, legitimacy, accountability, and equity move to the forefront of planning discourse. The evolution from early smart city infrastructures toward fully digitally mediated governance environments does not merely introduce new technical tools; it transforms decision-making architectures, redistributes institutional authority, and reconfigures the relationship between citizens and the state. In this transition, urban management increasingly relies on data-driven processes, predictive modelling, and algorithmic optimization, thereby reshaping how priorities are defined, resources allocated, and risks assessed.

Algorithmic systems and AI-driven analytics now influence domains ranging from mobility regulation and infrastructure maintenance to environmental monitoring and security management. Predictive tools can enhance administrative efficiency, support rapid responsiveness, and optimize complex urban flows. However, the growing reliance on automated decision platforms also raises critical concerns. When political choices are

embedded within technical systems, governance risks being reframed as neutral optimization rather than value-laden deliberation. As Yeung and Lodge (2024) argue, algorithmic regulation may introduce forms of opacity that complicate democratic oversight and blur institutional accountability. Decisions that affect public space, environmental distribution, or service provision may become difficult to scrutinize if embedded in proprietary or technically complex systems.

Figure 1: The IMDRF Conceptual Framework



These challenges acquire particular significance in Mediterranean contexts, where urban public space historically functions as a locus of civic expression, collective identity, and political engagement. The piazza, the waterfront, and the neighborhood street are not merely spatial infrastructures but arenas of social negotiation and democratic life. Consequently, digital governance in Mediterranean cities must be especially attentive to transparency, inclusiveness, and public legitimacy. Technological systems should not displace deliberative processes but rather support them. Human-centered digitalization frameworks emphasize precisely this principle: digital infrastructures must augment human agency, enabling informed participation and collaborative problem-solving rather than substituting political judgement (Saha A., 2025).

Within this perspective, several ethical dimensions require systematic integration into urban digital strategies. First, transparency and explainability are foundational. AI-driven urban systems must generate interpretable outputs that allow policymakers, professionals, and citizens to understand the assumptions and trade-offs embedded in algorithmic models. Without explainability, trust erodes and democratic deliberation weakens. Second, data justice and inclusion are critical to preventing digital transformation from reinforcing socio-economic divides. Participation platforms, sensor networks, and data-driven services must be accessible to diverse populations, including those with limited digital literacy or infrastructural access. Inclusive engagement mechanisms and proactive outreach are therefore integral components of ethical digital urbanism.

Third, cultural sensitivity is essential in historically layered Mediterranean environments. Digital planning tools often originate in globally standardized smart city models that prioritize efficiency and scalability. Yet Mediterranean urbanism is deeply shaped by place attachment, informal practices, and localized cultural identities. Digital systems must therefore adapt to contextual realities rather than impose uniform technological templates. Fourth, democratic accountability must remain clearly anchored within institutional structures. While AI-assisted systems may inform decision-making, they cannot replace political responsibility. Clear lines of authority, regulatory oversight, and mechanisms for contestation are necessary to ensure that algorithmic support does not translate into technocratic displacement of democratic governance.

These ethical considerations signal a broader paradigm shift: the movement from a technocratic smart city model toward digital humanism in urban planning. Digital humanism reframes technology as embedded within social, cultural, and normative contexts rather than as an autonomous driver of urban transformation. In this paradigm, artificial intelligence becomes a collaborative analytical partner that enhances evidence-based deliberation. Digital twins function as collective decision-support environments where alternative scenarios can be evaluated transparently. Immersive platforms serve not merely as visualization tools but as arenas for democratic co-production of space.

For Mediterranean urban regeneration, this shift is particularly consequential. Historical continuity, social density, and cultural memory demand context-sensitive approaches that respect lived experience and community identity. A purely technocratic digital modernization risks undermining precisely the qualities that make Mediterranean cities resilient and vibrant. By contrast, a human-centered digital framework recognizes that environmental intelligence, spatial modelling, and immersive participation must operate within ethical governance structures grounded in democratic values.

Ultimately, sustainable urban regeneration in Mediterranean cities depends not solely on technological modernization but on the cultivation of digitally enabled civic ecosystems. Such ecosystems integrate environmental analytics, multi-scalar spatial intelligence, participatory immersion, and accountable governance into a coherent and adaptive strategy. In this model, digital infrastructures do not supersede public life; they reinforce it. Technology becomes a mediator between data and deliberation, between modelling and memory, and between optimization and justice. Through this integration, Mediterranean urbanism can navigate the complexities of climate vulnerability, socio-economic inequality, and cultural preservation while sustaining democratic legitimacy in an increasingly digital age.

CONCLUSIONS

This study has examined the evolving relationship between sustainable urban regeneration and digital transformation in Mediterranean cities, situating artificial intelligence, BIM, digital twins, and immersive technologies within a broader socio-technical and cultural framework.

By integrating environmental, spatial, participatory, and governance dimensions, the paper has argued that digital urbanism must move beyond technological optimization toward human-centered and context-sensitive regeneration strategies.

Mediterranean urban environments present distinctive structural and cultural characteristics: historical continuity, compact morphology, dense social interaction, and strong public space traditions. These attributes simultaneously strengthen urban resilience and complicate environmental adaptation. Climate vulnerability, particularly heat stress, water scarcity, and infrastructure strain, intersects with socio-economic inequalities and heritage preservation constraints. As a result, sustainable urban regeneration in Mediterranean contexts demands multi-layered approaches that reconcile ecological performance, cultural continuity, and social inclusion.

The analysis demonstrated that digital technologies significantly enhance the capacity of cities to address such complexity. BIM systems contribute to lifecycle sustainability management and resource efficiency, supporting informed design decisions and integrated infrastructure coordination. Digital twins expand this capacity by enabling real-time simulation, environmental monitoring, and scenario modelling for climate adaptation and infrastructure resilience. Artificial intelligence further strengthens urban adaptability through predictive analytics, optimization of mobility systems, and data-driven governance. Immersive technologies, including VR and AR, extend digital urbanism into the participatory domain by fostering experiential understanding and collaborative design.

However, the comparative analysis of Barcelona, Athens, Naples, and Málaga underscores that technological deployment alone does not guarantee sustainable outcomes. Barcelona's Superblocks initiative illustrates how digital monitoring and data analytics can reinforce pedestrian-oriented, human-scale urban design. Conversely, the Athens Ellinikon redevelopment reveals tensions between advanced digital modelling and broader issues of inclusiveness and governance transparency. These cases confirm that digital transformation must be embedded within participatory planning cultures and accountable institutional frameworks.

The Integrated Mediterranean Digital Regeneration Framework proposed in this paper conceptualizes sustainable digital urbanism as a four-layered system: environmental intelligence, spatial integration, participatory immersion, and ethical governance. This framework contributes to the literature by synthesizing smart city technologies with Mediterranean socio-cultural specificity and resilience theory. Rather than replicating universal smart city models, the framework advocates for adaptive digital ecosystems tailored to historically layered, climate-vulnerable urban contexts.

Crucially, the study highlights the need to address ethical and governance implications of algorithmic urbanism. As AI-driven systems increasingly influence urban decision-making, issues of transparency, accountability, and data justice become central to democratic legitimacy. Human-centered digitalization approaches provide a normative anchor for aligning technological innovation with civic values, ensuring that digital tools augment rather than replace collective deliberation.

The theoretical contribution of this research lies in reframing digital transformation as a socio-technical mediator between environmental resilience and cultural sustainability. In Mediterranean cities, where identity, memory, and public space play foundational roles, digital urban regeneration must remain sensitive to lived experience and social cohesion. Technological sophistication must be balanced with inclusiveness, accessibility, and participatory depth.

Future research should further explore empirical performance metrics of AI-integrated regeneration projects, longitudinal impacts of immersive participation tools, and governance models capable of ensuring algorithmic accountability. Additionally, comparative studies

beyond the Mediterranean basin may test the transferability of the proposed framework to other culturally dense and climate-sensitive regions.

Ultimately, sustainable urban regeneration in Mediterranean cities depends not solely on technological capability but on the cultivation of integrated digital-human ecosystems. By embedding environmental intelligence, spatial modelling, participatory immersion, and ethical governance within coherent planning strategies, Mediterranean urbanism can evolve toward resilient, inclusive, and culturally grounded futures.

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