

Applications of System Dynamics in Smart Cities: A Systematic Review

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ABSTRACT

Despite the growing availability of urban big data, smart city initiatives often fail due to unforeseen feedback loops. This study utilizes a systematic review of 22 peer-reviewed articles to evaluate the efficacy of system dynamics (SD) in mitigating these failures. The paper categorizes current SD applications. While governance studies rely on qualitative causal loop diagrams to map soft variables, energy and mobility research is increasingly adopting hybrid quantitative simulations. The findings indicate that these hybrid models are essential for predicting critical “tipping points.” The review concludes that SD provides the necessary temporal framework to manage the lag between investment and sustainability, offering specific policy recommendations to avoid premature project cancellation.

KEYWORDS

Smart Cities, System Dynamics, Systematic Review, Urban Sustainability, Smart Governance, Policy Simulation, Causal Loop Diagrams, Stock and Flow Diagrams

INTRODUCTION

The 21st century has been characterized by a swift and unprecedented pace of urban growth (Chan, 2019). The United Nations states that 55% of the global population lives in urban regions, with expectations that this number will rise to 68% by 2050 (UN, 2019). This demographic change exerts a significant strain on urban infrastructures, requiring improved management of resources, energy, mobility, and governance. As a result, the idea of smart cities (SCs) has surfaced as a leading model for future urban development (Caragliu et al., 2013; Giffinger et al., 2007). While definitions differ, SC is typically defined as an urban environment that employs information and communication technologies (ICT) to improve the quality and efficiency of urban services like energy, transportation, and utilities, which in turn lowers resource usage and overall expenses (Caragliu et al., 2013).

Initial notions, like those proposed by Giffinger et al. (2007), identified six fundamental dimensions of SC: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Research highlights that a city is more than just a set of technological tools. As

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observed in broader organizational research, the failure to implement complex systems often stems from a strong technological orientation that overlooks the specific cultural and methodological needs of the environment (Bureš, 2006). It is a sophisticated network of systems in which human capital, social capital, and conventional infrastructure converge (Nam & Pardo, 2011).

The deployment of sensors and the Internet of Things devices offer city managers extensive data, but having this data does not inherently lead to effective policy (Tang & Ho, 2019). Urban systems are fundamentally intricate, marked by non-linear connections, feedback mechanisms, and time delays between actions and outcomes (Ompad & Tozan, 2019). Frequently, conventional linear planning approaches do not account for these dynamics (Batty et al., 2012). While conventional linear planning fails to capture urban complexity, other non-linear paradigms such as agent-based modeling (ABM) and artificial intelligence (AI) techniques have also gained prominence. ABM excels at simulating bottom-up, heterogeneous individual behaviors (Chimeh & Richmond, 2018), while AI approaches offer superior predictive power based on historical data patterns (Mole, 2025). However, these methods often face challenges regarding computational opacity (black box nature) or high data dependency. In contrast, system dynamics (SD) offers a unique macro-level perspective, focusing on the feedback structures and causal loops that drive systemic behavior, making it particularly distinct for strategic policy design where structural transparency is required. For example, expanding roads to alleviate congestion often leads to increased traffic (a rebound effect), or enhancing efficiency in one area (such as energy) can have unintended impacts in another (like social equity; Sterman, 2002). Furthermore, the urgency of these dynamics has intensified in the post-pandemic era. City leaders are no longer solely focused on efficiency; they now face high-stakes challenges regarding urban resilience and the capacity to withstand systemic shocks. In this context, the integration of AI-driven digital twins and real-time data management becomes not just a technological upgrade but a survival mechanism for modern urban infrastructure.

As cities become more interconnected through digital layers, the risk of policy resistance increases (Colding et al., 2019). Therefore, scholars argue that for a city to be truly smart, it requires not only data collection but also dynamic modeling capabilities that can simulate the long-term behavior of these complex socio-technical systems (Wolstenholme, 1986).

To address this complexity, SD has resurfaced as a critical methodological tool. Originating from the work of Jay Forrester in the late 1960s through his book *Urban Dynamics* (Forrester, 1970), SD provides a framework for mapping the feedback structures (stocks and flows) that drive system behavior. Unlike static statistical models, SD allows researchers and policymakers to simulate what-if scenarios over decades, making the long-term side effects of today's decisions visible (Sterman, 2001).

Despite its utility in strategic framing, the application of SD is not without challenges. The methodology is frequently critiqued for its high data intensity when moving from qualitative mapping to quantitative simulation. Reliable longitudinal data required for calibrating stocks and flows is often unavailable in fragmented urban environments. Furthermore, SD models are sensitive to their underlying structural assumptions (Wiens et al., 2009). Unlike purely data-driven approaches, SD relies heavily on the mental models of system designers, which can introduce bias if not rigorously validated against empirical evidence. These limitations underscore the necessity of examining how contemporary research validates these models and integrates them with other quantitative frameworks. Contemporary research is actively working to address these challenges, for instance, through hybridization with other methods.

In the context of the modern SC, SD is evolving. It is no longer just a tool for theoretical policy analysis but is increasingly hybridized with hard engineering methods such as life cycle assessment (LCA), material flow analysis (MFA), and ABM (Batty et al., 2012). This integration allows for a holistic view that combines the precision of engineering data with the strategic breadth of policy simulation (Harrison et al., 2010).

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