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Urban Modeling Traditions: A Literature Review on Methods and Applications

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**Introduction:**
Cities are complex systems with interconnected economic, household, transportation, infrastructure, and environmental subsystems, where interventions in one domain cause cascading effects. Past modeling approaches in complexity science, economics, and land-use-transportation models have often operated in isolation. To better inform policy and capture cross-sector feedback, integrated models are essential for understanding urban growth, decline, and the unintended consequences of interventions. This review calls for comprehensive integration.

**Approach:**
Employing a pragmatic scoping review, this paper synthesizes insights from diverse scholarly communities on leveraging models for urban systems. Authors searched Google Scholar, JSTOR, and ArXiv for peer-reviewed publications (2000–2025) using Boolean strategies and AI-assisted queries. Focusing on dynamic, quantitative model-informed approaches, the review outlines dominant methodologies, convergences, divergences, and practical recommendations to enhance urban policy design across interdisciplinary fields.

**Results:**
To varying degrees, complexity science, SD, economics, land use and transportation, and urban sustainability models account for interdependencies within urban systems. Research communities vary significantly in model boundary, aggregation level, data reliance, and stakeholder engagement. Future work should cautiously expand model boundaries, balance model detail with clarity and performance, prioritize empirical calibration for credibility, and strategically enhance stakeholder involvement to ensure policy relevance.

**Discussion:**
Fragmented modeling traditions hinder the ability to capture urban connectivity that is essential for effective policy design. Interdisciplinary integration, empirically grounded models, stakeholder engagement, qualitative insights, and scenario analysis are key for any future urban modeling endeavors that aim to support comprehensive, realistic, and actionable urban policy design.

# Urban Modeling Traditions: A Literature Review on Methods and Applications

**Abstract:** Urban policy and planning decisions must contend with the dynamic complexity of cities – interdependent systems with non-linear, emergent behaviors that make outcomes difficult to predict. Dynamic modeling approaches, like those deployed in complexity science, system dynamics, urban economics, and land use and transportation modeling offer useful tools for cities as they navigate complex realities. Yet, these disciplines evolved in relative isolation, limiting cross-disciplinary integration. This paper reviews and synthesizes key modeling approaches, evaluating their strengths and limitations in capturing urban complexity. We explore how different methodologies have been applied to urban growth, infrastructure investments, housing markets, environmental sustainability, and transportation systems, highlighting areas of convergence and divergence. The review underscores the need for models that account for long-term dynamics, cross-sector policy interdependencies, and unintended consequences. This synthesis aims to advance interdisciplinary learning and inform next-generation urban models that better support decision-making in the face of rapid global urbanization.

## Introduction

Cities are fundamentally complex systems, composed of tightly interwoven economic, household, transportation, infrastructure, and environmental subsystems. Decisions in one domain reverberate across others, creating feedback loops and emergent behaviors that challenge linear thinking (Gallotti et al., 2021). Urban growth and decline, for instance, emerge from myriad interactions: economic opportunities influence migration and land use; transportation networks shape development patterns and emissions; infrastructure investments alter real-estate markets; and environmental conditions feedback into public health and productivity.

What may appear as a straightforward intervention in one sector can thus trigger cascading effects throughout the urban system. Indeed, it is observed that government programs in complex social systems may yield results *opposite* to those intended when important feedback mechanisms are overlooked (Forrester, 1971). For example, a city's effort to relieve traffic congestion by widening highways may initially speed up traffic, but it also incentivizes more driving and longer commutes. Over time, the added road capacity induces additional travel demand, ultimately filling up the roads again, eroding initial congestion relief, and potentially even making the problem worse (Duranton & Turner, 2011). Similarly, policies aimed at one aspect of urban life – such as subsidizing housing, restricting land use, or attracting industries – may inadvertently strain other systems like transport or public education. This complexity motivates the need for modeling approaches that can capture cross-sector feedback and long-term dynamics beyond the scope of any single-discipline.

This paper starts with a brief synopsis of the last 50 years of model-informed urban studies. We then conduct a scoping review of the recent research in complexity science, system dynamics, economics, land and transportation use, and environmental disciplines deploying dynamic models to advance urban understanding. We discuss the gaps and limitations of each tradition and conclude with recommendations for the more effective use of models in planning policy within the complex urban systems.

## Modeling Urban Dynamics: Integration and Fragmentation

Jay W. Forrester's landmark book *Urban Dynamics* (1969) was one of the first to explicitly model a city as a unified, dynamic system of interacting components. Forrester developed a simulation of a stylized city that included feedback loops between the population, housing, and business sectors. In an era when urban studies were often compartmentalized, *Urban Dynamics* introduced a radically new perspective on analyzing urban problems, treating the city as an endogenous system evolving over time. The model captured how housing stock, employment opportunities, and land use co-evolve, leading to patterns of growth, stagnation, and decline. Crucially, it demonstrated how policy interventions could have counterintuitive effects due to the city's internal dynamics. For example, it suggested that building large amounts of low-income housing could inadvertently worsen urban decline unless balanced by business growth because excess housing without jobs reduced a city's overall attractiveness. Such conclusions were controversial at the time, but they vividly illustrated Forrester's key insight: urban ills like unemployment or crime stem from complex feedback structures rather than one-way cause-effect chains.

In the decades following *Urban Dynamics*, urban modeling branched into multiple modeling traditions, often evolving in isolation within different academic and professional communities (Gallotti et. al., 2021). While system dynamics practitioners continued to build feedback-rich simulation models of urban processes (Alfeld & Graham, 1976) parallel traditions grew in urban planning, economics, complexity science, and transportation engineering. Each tradition brought its perspectives, methods, and simplifications, typically focusing on particular subsets of the urban system. As a result, the literature on urban modeling became fragmented across disciplines, with planners, economists, and others developing separate toolkits and rarely cross-referencing each other's work, resulting in insights that were often siloed. For instance, a transportation model might treat travel behavior in detail yet omit housing market feedbacks, whereas an economic model could capture land and housing markets but leave out the transport network or environmental impacts. Over time, researchers have produced a rich array of models tailored to specific questions, but the lack of integration means that no single approach has fully accounted for the cascading effects of urban complexity.

Urban planning and land-use modeling advanced along a different path from system dynamics. Planners in the 1960s and 1970s developed spatial-economic models to forecast urban growth and land development, emphasizing the geographic distribution of activities. A notable example was the Lowry model (Lowry, 1964) which became a standard structure in this literature. Lowry's framework used input–output style equations and gravity-based spatial allocation to link employment, housing, and travel, providing planners with a tool to examine how jobs and residences are located across a metropolitan area. Its relative simplicity and focus on spatial equilibrium contrasts with Forrester's focus on transient dynamics, yet both sought to represent the interplay of housing, jobs, and transport in cities. Throughout the 1970s, however, large-scale integrated models faced skepticism which questioned whether such models target real problems, could be built and empirically verified, and could offer meaningful insights (Lee, 1973). Consequently, many integrated land use–transport models retreated to academia, while planning practice primarily relied on narrower tools such as travel demand models and demographic forecasts. It was not until the late 1990s that interest in broad-boundary urban modeling revived, aided by better data, faster computing, and pressing policy issues requiring long-term insights (Waddell, 2002).

In parallel, urban economics developed its own modeling tradition. Economists approached the city through theories of market equilibrium and optimizing households and firms, producing analytical models of urban land use, pricing, and migration. Classic urban economic models (e.g. Alonso's bid-rent theory (1964) and its successors) depict how rational households and firms make location choices balancing land costs, transport costs, and wages, yielding an equilibrium urban form. These models provided deep insight into the economic drivers of city structure, such as why land prices and densities decay with distance from the city center. However, they often made simplifying assumptions (e.g. instant equilibrium, representative agents, etc.) that set aside the dynamics of cities as they transition to new states in light of various interventions. Resulting models often excel at capturing equilibrium outcomes of tight feedback among households, firms, and buildings but may treat technology, infrastructure, or environmental impacts as exogenous. Moreover, they may side-step path-dependent processes that determine the evolutionary trajectories of real cities. Overall, the urban economics tradition has significantly expanded our understanding of supply–demand interactions in cities, even as it developed largely separate from the simulation-oriented approaches in planning and system dynamics.

By the late 20th century, a new wave of complexity science further broadened the landscape of urban modeling. Scholars inspired by complexity theory and nonlinear dynamics began to frame cities as complex adaptive systems made up of many interacting agents. Pioneers like Michael Batty argued that urban phenomena from traffic jams to land-use patterns are emergent results of countless decentralized decisions, best understood with bottom-up modeling approaches (Batty, 2007). Complex systems researchers introduced techniques such as cellular automata models of urban growth, in which simple local land-use rules can generate realistic city layouts, and agent-based models (ABM), in which individual households, developers, or travelers are simulated as autonomous agents interacting over time. These models embraced stochasticity, adaptation, and spatial heterogeneity that traditional models found hard to incorporate. Pushing beyond the aggregate style of earlier approaches, complexity models showed how surprising macro-level patterns, including urban sprawl, segregation, and congestion waves, can emerge from micro-level behaviors. They also borrowed ideas from network science to study urban infrastructure – transportation, power, water – as interdependent networks whose failures can propagate unexpectedly. Another research stream used simpler models to quantify the empirical scaling patterns in cities: how various characteristics, from income and innovation to infrastructure, scale with the size of cities. While complexity-oriented urban modeling gained its own following (often in geography or interdisciplinary circles), it too tended to evolve apart from the older system dynamics and economic planning models. By the 2000s, a researcher comparing the system dynamics literature and, say, an agent-based urban model might find few common references despite their shared subject matter and many overlapping feedback mechanisms.

Meanwhile, transportation modeling became a well-established specialty with standardized methods. Travel demand forecasts typically rely on the classic four-step model (trip generation, distribution, mode choice, route assignment) or more advanced microsimulation of travel behavior. These tools are crucial for infrastructure planning and policy (e.g., evaluating a new transit line or highway) and capture detailed travel dynamics and model shifts. However, transport models oversimplify land use, economic feedback, and environmental feedback. For example, a regional travel model might assume a fixed distribution of population and jobs (or use an external land-use model), thereby *excluding* the possibility that improved transport access will itself reshape where people live and work over time. This underscores how specialized models can miss the two-way interactions present in real cities: transportation affects land development and vice versa. In practice, some integrated frameworks do couple transport and land use (and even environmental emissions) to predict long-run policy effects, but these integrated models were historically developed in relative isolation within the transport planning community.

By the early 21st century urban modeling knowledge had fragmented into distinct traditions. System dynamics offered insight into aggregate broad-boundary temporal dynamics; urban planning models provided spatial and policy-oriented simulations; urban economics yielded equilibrium theories and empirical insights; complexity science introduced novel representations of emergent urban phenomena; and transport engineering delivered sophisticated travel behavior models. Each tradition has informed key facets of urban complexity, yet each also has blind spots reflecting its disciplinary priorities. The consequence is that researchers and practitioners often talk past one another, lacking a common framework to address the full breadth of urban system challenges.

## Learning Across Urban Policy Models

The growing appreciation of urban complexity and the limitations of isolated approaches has led to calls for integrative modeling perspectives. If economic, transportation, infrastructure, and environmental factors are deeply interconnected, our analytical tools must be as well. This literature review is premised on the idea that bridging diverse modeling traditions can yield a more comprehensive understanding of urban systems than a singular approach. By examining work across system dynamics, urban sustainability, economics, complexity science, and land/transportation modeling, we seek to identify commonalities, complementary strengths, and gaps in these approaches. For example, one finds that different models often confront similar phenomena – congestion, housing affordability, emissions, equity – but emphasize different causal mechanisms, aggregation levels, and timescales. Mapping these perspectives side-by-side reveals where they converge or diverge. It also highlights what important dynamics might be missing in each: a system dynamics model might lack spatial resolution, whereas an economic model might omit feedback delays or transient behavior. Recognizing such gaps is a first step toward developing next-generation urban models that synthesize the insights of multiple traditions.

Ultimately, the motivation for this cross-disciplinary inquiry is practical. Urban policymakers today face multifaceted problems – climate change, resilient infrastructure, inclusive growth, mobility for all – that require accounting for far-reaching ripple effects of each policy option. The realities of urban governance also require sensitivity to transient dynamics: it is not enough to suggest that a policy offers net positive outcomes, if such equilibrium is achieved in 30 years time. Models intended to inform policy need to capture the web of interdependencies, potential unintended consequences, and the short-vs-long term tradeoffs that policy actions entail. This review attempts to facilitate cross-community learning towards the next generation of analytically rigorous, empirically grounded, and policy-relevant models that could ex ante inform how a host of urban policies might play out through interconnected economic, transport, infrastructure, and environmental pathways.

The next sections offer a more detailed literature review of these modeling paradigms. The research question examined in this scoping review is, “What features distinguish modeling approaches to urban complexity coming from complexity science, system dynamics, urban economics, land use and transportation, and urban sustainability; and what are the strengths and gaps in these methods?" In the following sections, we review each tradition's approach and review a selected set of representative and impactful model-based articles. In tables (Appendices A, B, C, D, E), we summarize research questions, methods, data, findings, and policy implications of these papers and offer narrative integrations of those findings in the body of the paper.

## Methods

This paper utilizes a pragmatic scoping literature review methodology to identify, synthesize, and interpret insights from various communities in leveraging models to examine urban systems and policy design. Scoping reviews are often conducted to provide an overview of the existing literature, knowledge gaps, and outline the evidence of scholarly work on emerging topics (Peters, Godfrey, et al., 2020) with a focus on future research questions (Arksey & O'Malley, 2005). Our broader research question, including and extending beyond the boundaries of this paper, is: "How can models be best utilized to inform effective policy in urban systems?" A structured approach informing this ultimate goal was adopted rather than a formal systematic review that may cast a wider net but offer less focused insights on a motivating question. To make comparisons feasible and the scope manageable, the review focuses on dynamic, quantitative model-informed approaches that elucidate systemic interconnections within urban contexts.

To systematically identify relevant literature, structured searches were conducted in Google Scholar, JSTOR and ArXiv using a Boolean search strategy. Search strategies combined key thematic terms tailored to each disciplinary area of focus. Searches were filtered for peer-reviewed publications from 2000 to 2025 to ensure contemporary relevance. Studies were included if they met the following criteria:

1. Peer-reviewed empirical studies or seminal preprints (ArXiv).
2. Relevance to urban studies in complexity science, urban economics, land-use and transportation modeling, system dynamics, or urban sustainability.
3. Quantitative analyses, model-informed research approaches, or computational modeling explicitly applied to urban contexts.
4. Articles must be accessible in full text through institutional subscriptions and published in English.

Given the breadth and depth of the literature examined, artificial intelligence-assisted searches were also employed to enrich the selection process. Queries were systematically run through platforms, including GeminiAdvanced, ChatGPT, and DeepSeek using tailored prompts for our selected urban system sectors. The resulting literature set was evaluated based on its methodological fit and relevance to the synthesis of insights from distinct modeling communities. While the approach adopted was structured and broad, it did not employ the full methodological rigor associated with systematic literature reviews. Instead, it prioritized thematic coherence and practical relevance for urban policy and planning contexts.

In the following sections, we introduce the dominant approaches to model-informed urban policy, outlining their key methodologies, applications, areas of convergence, points of divergence, and limitations. The discussion that follows explores the practical implications of integrating model-informed research into urban policy analysis, offering recommendations for researchers and policymakers.

# Complexity Science

Complexity science in urban planning applies principles of nonlinear dynamics, feedback loops, and emergence to understand how cities function as complex adaptive systems. This approach highlights self-organization, path dependency, and the interplay of multiple agents, including residents, businesses, and infrastructure, whose local actions combine to produce city-wide patterns. Techniques like agent-based modeling and network analysis reveal how small changes in behavior in one area of the system can generate far-reaching shifts in urban form and function. This approach encourages policymakers and planners to embrace uncertainty, experiment with adaptive strategies, and cultivate resilience, recognizing that city systems evolve dynamically. Two strands of this research, scaling laws and complexity models, may be distinguished. Appendix A provides a detailed review of key papers in these traditions, with a narrative summary below.

The existence of universal scaling laws, meaning that certain characteristics of cities such as innovation, productivity, or infrastructure efficiency, change predictably with population size, presents a key finding from the first strand of this literature. Researchers like Bettencourt et al. (2007) and Hong et al. (2020) find consistent patterns across different cities: social and economic indicators such as wages, innovation, and wealth creation scale faster than population growth, termed “superlinear scaling.” Unlike social and economic indicators, the physical infrastructure of a city scales at a slower rate, reflecting economies of scale. Hong et al. (2020) also demonstrate a developmental pathway in which cities shift from manual-labor-based to more innovation- and knowledge-intensive economies around a critical population tipping point of 1.2 million. These findings highlight a fundamental advantage of urban density: larger cities stimulate innovation and productivity; however, they also simultaneously encounter heightened problems such as transportation congestion and decreased housing affordability.

Despite strong consensus on scaling patterns, researchers diverge when analyzing specific outcomes, notably concerning inequality and city growth dynamics. Mora et al. (2021) complicate the uniformly beneficial scaling effects narrative (Bettencourt et al. 2007) by demonstrating pronounced inequalities. They find that wealthier segments benefit disproportionately from urban scale advantages while low-income residents experience limited income gains and declining affordability. This divergence stresses the need for urban planners and policymakers to explicitly integrate social equity considerations into strategies for managing growth. Policymakers should recognize that aggregate prosperity indicators can mask underlying disparities, suggesting more nuanced interventions to ensure benefits reach all urban residents.

While scaling literature focuses on similarities across cities, a related stream emphasizes evolutionary dynamics and path-dependency, shaping distinct trajectories and resulting urban hierarchies. Researchers, including Bretagnolle et al. (2009), Bettencourt et. al. (2010), and Raimbault & Pumain (2020), argue that historical contingencies, innovation diffusion, and regional interactions shape long-term urban growth patterns. Cities within broader urban systems evolve through cycles of innovation adoption, competitive pressures, and diffusion processes, reinforcing hierarchical differentiation. Specifically, Bettencourt and colleagues (2010) show that many core indicators like gross economic output, per capita income, patenting rates, and even crime follow consistent power law relationships with city population. Beyond cross-sectional patterns, as a city’s population grows, its wealth and innovative outputs often rise disproportionately, while crime also tends to increase at a faster-than-linear rate. The authors introduce Scale-Adjusted Metropolitan Indicators (SAMIs), which factor out population size to highlight each city's "true" performance relative to peers and explain differing outcomes. Their analysis of decades' worth of data suggests that these SAMIs exhibit long-term stability, meaning cities that are high-performing (or under-performing) in, for example, innovation or income tend to remain that way for many years. Bettencourt et al. also find only modest geographical correlations (cities close together) are not necessarily alike, indicating that truly kindred urban areas share socioeconomic histories and growth patterns more than they share location. These insights highlight the key question of how a city may get to the performance frontier on SAMIs in some domain, a question not directly informed by cross-sectional patterns in scaling studies.

Practically, findings from Bretagnolle et al. (2009), Bettencourt et. al. (2010), and Raimbault & Pumain (2020) imply that significant urban change, from improving incomes to reducing crime, usually require sustained, long-term interventions capable of shifting a city's local trajectory over decades rather than years. Further, it serves to quantify the long-term forces that produce uneven growth and concentration in certain cities. By measuring the ways transport innovations, political shifts, and economic changes alter a city's reality, this body of work can produce more effective forecasts to guide urban decision making. Additionally, this type of analysis assists policymakers and academics alike in parsing the effects of city population size from true local performance and begin comparing "apples to apples."

More divergence in the field arises when it comes to interpreting city-size dynamics. Xu and Harriss (2010) show that city growth is influenced by spatial and temporal autocorrelation – cities do not evolve independently but rather in interdependent clusters shaped by historical growth patterns and spatial proximity. These perspectives diverge from studies emphasizing a consistent hierarchical concentration of innovation within the largest cities. For urban planners, this suggests the need to develop nuanced, opportunity-sensitive strategies rather than generic growth policies. Infrastructure investments and regional planning should explicitly acknowledge spatial interdependencies and historical trajectories, guiding strategic planning with detailed consideration of local and regional contexts.

Another consideration for urban development comes from Barner et al. (2017). They quantify urban complexity and find that urban spatial structures characterized by higher entropy or complexity tend to be more adaptable, resilient, and responsive to uncertainty and future changes. A higher-entropy urban environment exhibits a greater variety in land use patterns, street configurations, and building types. A lower-entropy environment tends toward homogeneity, where similar building forms, singular land uses, or uniform block sizes predominate. Urban planners, designers, and academics thus benefit from rigorously employing complexity metrics (e.g., Shannon entropy, fractal dimensions, spatial diversity indices) in evaluating and guiding development projects.

Another example of complexity-inspired modeling is the work by Yang, Ko, and Cho (2024). They highlight the dynamic interplay of economic policies and spatial urban forms through an Oscillation and Wave Framework. They find tipping points where congestion thresholds alter urban forms from dense clustering to sprawling dispersion. This study reinforces the importance of integrated economic and spatial policy frameworks.

Complexity science offers a valuable lens through which to view urban systems but is not immune to criticism. Models in this field can be overly stylized, capturing general patterns of self-organization and emergence but often simplifying the diverse lived experiences on the ground. Furthermore, an emphasis on bottom-up interactions can further obscure the roles of power structures, institutional influences, and other top-down processes (e.g. politics) that shape cities. Finally, the relationship of these models with data varies based on the model type. Specifically, scaling law models are typically simpler and provide cross sectional (and occasionally time series) fit with data without attempting to match individual histories closely. The more detailed agent-based models may be well-informed by qualitative data, but are often too complex and computationally expensive to be formally estimated using quantitative data, adding more uncertainty to the reliability of their recommendations for specific communities.

Taken together, these diverse complexity-oriented studies share a broad recognition of cities as adaptive, nonlinear systems where policy actions inevitably reverberate through multiple subsystems, generating emergent outcomes often contrary to linear projections. Most scholars indicate that nuanced, locally tailored planning is essential for improving urban trajectories, but different studies point to different focus areas and methods for executing that vision. The literature also diverges notably in its interpretation of urban inequalities and growth trajectories. See Appendix A for a full summary table.

# System Dynamics

This section synthesizes more recent research applying system dynamics modeling to urban studies across urban dynamics, land use and transportation, and environmental modeling. This literature continues on the pioneering path charted by Forrester (1969) and his collaborators (Alfeld, 1995) and shows the continued value of SD modeling in cogently handling the feedbacks across urban sectors. Whether focusing on urban water supplies (Ghasemi et al., 2017; Gober et al., 2011), land use and carbon emissions (Feng et al., 2013), behavior change in adopting sustainable practices (Harich, 2010) or transportation policies (Cheng et al., 2015; Cox et al., 2017), these studies capture how demographic, economic, and infrastructure subsystems interact over extended time horizons.

Others have expanded the use of SD with complementary modeling techniques. For example, Chang and Ko (2014) demonstrate how multi-objective programming and SD can be jointly used to evaluate land-use strategies under uncertainty, while Wu and Ning (2018) couple SD with GIS mapping to reveal how different Beijing districts respond to policy changes impacting the long-term sustainability of urban economic growth, environmental protection, and energy consumption. Fu, Wu, Che, and Yang (2017) combine SD with the CLUE-S model to examine carbon emissions linked to land-use change in Shanghai, finding that preserving agricultural land and expanding green infrastructure can significantly mitigate emissions. Likewise, Güneralp, Reilly, and Seto (2012) illustrate a multiscalar perspective by integrating a regional SD model with a local spatial logit framework in the Pearl River Delta, achieving a 15–18% improvement in predicting urban land change compared to standalone models. Yeomans and Kozlova (2023) demonstrate how simulation decomposition (SimDec) can further extend SD-based approaches by enhancing both the sensitivity analysis and decision-making capabilities of urban models. Taken together, these studies highlight opportunities for hybrid methods that combine the strength of SD in capturing longer-term feedbacks with capabilities in data integration, optimization, and policy design coming from other modeling traditions.

One of the other strengths of SD models is their orientation toward policy analysis and decision-making. Scenario-based approaches are ubiquitous and typically used for analyzing and comparing the outcomes of various interventions. For example, Park et al. (2013) and Eskinasi, Rouwette, and Vennix (2009) both employ

SD modeling to address pressing urban development issues; self-sufficient city planning in the case of Park et al. and social housing market stability in the Haaglanden region for Eskinasi et al. Despite the different contexts, both studies leverage causal loop diagrams, simulation models, and stakeholder engagement to inform policy scenarios. Park et al. (2013) emphasize that role of investing in job creation and education welfare for building thriving communities in the long-term, while housing supply and service facility policies mainly facilitate early population stabilization. Eskinasi et al. (2009) concentrate on housing market transformations and the delicate trade-offs between renewal efforts and social housing availability. Although their focus is more on the interplay of social housing supply and migration flows, both studies arrive at the conclusion that policy decisions can induce unintended consequences if feedback loops and time lags are not carefully considered.

While SD studies typically incorporate some quantitative data in estimating model parameters (Sterman, 2000), the models often rely more on qualitative data, from stakeholder engagement as well as prior theory, to specify plausible structures. Moreover, taking a fully endogenous view, the models rely less on data inputs to generate various outputs. These architectural choices may create a challenge in the face-validity of models, specially in application areas where other research communities integrate highly detailed data into models. Some of these challenges may be addressed by incorporating methodological advances from neighboring domains to better integrate quantitative data into SD models. Another path taken by some SD researchers is to leverage conceptual transparency of the models, and the engagement of stakeholders into the modeling process, to enhance the impact of modeling projects in the real world. This feature can be further adopted by other modeling communities to enhance the impact of model-based policy design. Finally, the more aggregate conceptualizations in SD lead to more variance in the quality of models, where well-designed models allow for capturing similar core mechanisms (as in a more-detailed complexity oriented model) with orders of magnitude less computational costs and more transparency. On the other hand, one may find SD models in the literature that lack robustness and would not correspond closely with the empirical regularities on the ground.

# Urban Economics

In this field, dynamic models capture how economic agents (households, firms, and governments) interact over time to shape urban growth, land use, and resource allocation. These models integrate spatial factors like real estate markets and transportation networks with behavioral assumptions about consumption, investment, and migration. By incorporating feedback loops – how infrastructure investments spur development, which in turn influences tax revenues, for example – dynamic urban economic models shed light on evolving market conditions, housing affordability, and regional competitiveness. These models often use equilibrium assumptions to simplify the analysis and focus it on the first-order effects of each exogenous change after different interactions settle down in equilibrium. Economists use these tools to evaluate the long-term impacts of economic policies and to study how cities respond to shocks originating from technological disruptions, demographic shifts, or macroeconomic fluctuations.

The urban economists featured in this section generally agree that cities function like thriving ecosystems – or perhaps good dinner parties. When they're allowed to evolve naturally, driven by market forces and agglomeration economies (think of firms, workers, and ideas clustering together in vibrant hubs), cities become more productive and innovative. Rossi-Hansberg and Wright (2007) and Glaeser and Gottlieb (2009) emphasize that urban development is largely a product of endogenous market dynamics, underscoring the role of density, firm clustering, and knowledge spillovers in driving urban productivity. There is wide agreement among these scholars that city size and structure ultimately balance agglomeration benefits with increased transit congestion and other urban disutilities like rising housing costs.

Based on this common understanding, urban economics scholars suggest that urban policymakers should prioritize investments in accessible infrastructure, such as transportation and housing, and adopt flexible land-use and zoning policies to accommodate organic growth rather than enforcing rigid restrictions that can undermine agglomeration's economic advantages. Gaubert (2018) and Hsieh and Moretti (2019) find compelling empirical evidence that restrictive zoning and overly stringent land-use regulations in productive urban centers hinder labor mobility and economic efficiency. Consequently, these authors advocate for reducing regulatory barriers to enable cities to realize their productivity potential and to improve national economic outcomes.

Yet, not every urban economist agrees on the degree to which urban agglomeration is truly beneficial. Candau (2011) challenges the assumption prevalent in other works – Glaeser and Gottlieb (2009), Davis et al. (2014) specifically – that agglomeration inherently maximizes human welfare. Candau argues instead that rising urban costs, such as commuting burdens and land rents, will negate agglomeration benefits, especially for low-skilled, immobile workers. He introduces the notion that strategic decentralization or dispersion might sometimes offer superior welfare outcomes compared to pure market-driven agglomeration. Authors like Behrens and Robert-Nicoud (2014) and Farrokhi (2021) explicitly model and acknowledge that larger cities, despite their productivity advantages, usually experience heightened income inequality due to competitive firm selection and skill-biased agglomeration processes. Their suggested remedies emphasize policies to enable high-quality education and skill development. In contrast, Glaeser and Gottlieb (2009) attribute rising urban inequality primarily to inadequate housing supply and restrictive land-use regulations. They suggest that reforms aimed at increasing housing availability would significantly alleviate inequality pressures.

These studies collectively imply that successful urban governance builds on reinforcing feedbacks like agglomeration and trade that contribute to a city's growth. But it also requires continuous monitoring of potential bottlenecks like congestion, inequality, and constrained housing and timely policy design to avoid a hard landing when each constraint becomes binding. Policymakers must balance interventions carefully, recognizing that unchecked growth will push the city toward its constraints. Similarly, overly restrictive regulations or misguided decentralization policies might undermine urban productivity and economic momentum. In short, cities flourish when policy planners act like thoughtful dinner hosts: providing just enough structure and support (i.e., good transportation, flexible zoning, affordable housing) so everyone can comfortably participate.

Beyond these general insights, details matter: each community faces a distinct set of opportunities for activating reinforcing feedback for growth and a distinct set of impending constraints on that growth. Customizing models could help each community find the right balancing act among the competing pathways for growth and bottlenecks.

Additionally, economic equilibrium models are subject to some limitations when it comes to capturing urban dynamics. These models assume rationality and perfect information, meaning that all agents, from firms to households, possess perfect information when making decisions that shape the economy. In reality, actors have limited cognitive resources and face information asymmetries, which can lead to decisions that deviate from the “rational” benchmark and hinder reliability of forecasts. For example, research shows many low income households do not migrate from under-performing cities when better opportunities are available to them elsewhere, thus limiting their own options. Moreover, the equilibrium assumption in these models leaves out critical transient dynamics which may well be more important than equilibrium effects in the overall utilities of residents, and the politics of change. Complementary modeling techniques that incorporate key insights and mechanisms of economic models but also account for heterogeneity, bounded rationality, and evolving market dynamics can build on an equilibrium model’s strengths to better reflect the complexities of real-world economies. See Appendix C for the full summary table.

# Land Use and Transportation

Land use and transportation modeling have a long history of mutual influence and shared methods (Putman, 1983), which has led to the development of common land-use-transport (LUT) models. In essence, how land is used – where people live, work, and shop – shapes travel demand. Changes in transit systems involving new roads, transit lines, etc., can alter patterns of development and the distribution of households and firms. Recognizing this two-way interaction has spurred the creation of comprehensive frameworks starting with the classic Lowry model and evolving to other established models such as MEPLAN, PECAS, and UrbanSim that incorporate both land use changes and transportation performance into a single system.

The literature reviewed on land use and transportation modeling reveals notable areas of convergence, particularly in their shared interest in the dynamics of urban expansion, spatial distribution, and the interactions between infrastructure investments and land use patterns. Both streams recognize the importance of integrated modeling to inform sustainable urban policy decisions, although their approaches and focal points may differ. Convergence is clearly evident in works such as those by Waddell (2011), Kryvobokov et al. (2013), Pinto, Antunes, and Roca (2021), and Zhu et al. (2018), which emphasize the value of integrated land-use and transportation interaction (LUTI) models. These authors collectively highlight the need for models that incorporate real-time data and computational efficiency to effectively support urban planning and policy analysis. Similarly, Basu, Ferreira, and Ponce-Lopez (2021) from the transportation literature stress the potential of synthetic virtual cities as sandboxes for exploring land-use and transport interactions, aligning closely with the integrated modeling objectives discussed by Waddell (2011) and Zhu et al. (2018). Authors from both fields heavily utilize agent-based or micro-simulation methods to reflect complex urban dynamics and individual decision-making processes. Li and Liu’s (2007) multi-agent cellular automata model and Hammadi and Miller’s (2021) agent-based microsimulation framework illustrate how these methods enhance predictive accuracy by simulating individual behaviors in response to policies and infrastructure changes.

However, these literatures do not always align in their level of aggregation. Daganzo (2007) prioritizes macroscopic models of congestion dynamics, exemplifying network-level aggregate analysis and the use of macroscopic fundamental diagrams (MFDs). Such models focus on broader network flows, traffic control, and congestion management rather than detailed spatial land-use transformations. On the other hand, the land-use literature, as represented by Anas and Rhee (2006) and Deal and Schunk (2004), typically centers on the spatial distribution of economic activity, residential developments, and the environmental impacts of urban sprawl. Along the same lines, Long, Mao, and Dang (2009) and Pinto et al. (2021) adopt more localized, cell-level or parcel-specific scales, emphasizing policy interventions that directly influence land conversion and urban development patterns rather than regional economic dynamics.

Ultimately, these areas of convergence and divergence suggest complementary strengths within the literature, with integrated modeling frameworks increasingly bridging gaps between them. A continued emphasis on linking microscale urban phenomenon with land-use and transportation dynamics is likely to foster further interdisciplinary integration, providing policymakers and urban planners with robust decision-making tools. For instance, Zhu et al. (2018) proposed an integrated framework within SimMobility that accounts for behaviorally rich simulations across three distinct scales: rapid traffic operations in the short term, transit model choice and route selection in the mid-term, and slower moving, long-term decisions such as residential locations, job and school assignments, vehicle ownership, and real estate development. While considering dynamics across these three temporal scales is seemingly relevant to urban planners, limited studies have attempted modeling with such behavioral depth across multiple time horizons. Basu et al. (2021) work to create virtual cities and learning environments similarly offers relevant model-informed insights for practical application. Their framework for transforming simulated transit dynamics into realistic urban environments can shape the creation of serious games, flight simulators, or other model-based learning tools. Additionally, their proposal for an open-source, transferable platform could inform the development and broader application of urban simulation.

While these models, and the field generally, have long been used to help planners understand the interplay between how cities grow and how people move, there are a range of limitations associated with this approach. Many models traditionally focus on housing and mobility metrics, sometimes at the expense of environmental impacts, equity concerns, or public health outcomes. Behavioral factors, including a population's inclination towards a mode of transport – biking, car, public transit – are frequently left out of computational modeling, as well. These decisions often involve trade offs like cost, time, comfort, and personal safety that are not always captured in a model but evolve endogenously over time and thus change the utilities and choices in the longer time horizons.

Relatedly, it is common for these models to encounter data and calibration challenges. The more detailed models carry significant computational burdens that limit calibration. Moreover, these models often require detailed data that many urban areas do not capture or publicly report. This can lead to uncertainties in model outputs and reduce their reliability in policy contexts. Finally, while we've tried to limit our scope in this section to dynamic models, the vast majority of traditional models often rely on equilibrium or optimization frameworks that do not account well for how land use and transportation interact and coevolve. The slow, often non-linear changes in urban form and travel behavior can be challenging to incorporate in this type of modeling, and thus limits the model's predictive power and use for long-term planning. As a result, there is a growing emphasis on methods to better calibrate models, and integrated assessment frameworks that include environmental, social, and political factors. See Appendix D for the full summary table.

# Urban Sustainability

Environmental dynamic models in urban contexts combine methods from environmental science, urban planning, geography, and computational modeling to analyze environmental outcomes in urban communities. By simulating phenomena such as air pollution dispersion, urban heat islands, stormwater runoff, and land-use change, these models trace the impact of urban design and evolution on various environmental outcomes. This field is tightly connected to data, from satellite imagery to GIS layers, that can be incorporated as input to simulation models. Policymakers use these simulations to evaluate interventions, anticipate risks (e.g., flooding, pollution spikes), and guide sustainable urban growth.

The literature compiled in the table (see Appendix E) represents a rich diversity of modeling approaches aimed at addressing the interplay between urban development and environmental sustainability. Several studies converge on the need to integrate socio-economic dynamics with ecological processes in order to provide more realistic simulations for urban growth and its environmental trade offs. This approach, argued for by Alberti & Waddell (2000), Xu & Coors (2012) and Mercure et. al. (2016), can provide more realistic simulations and offer increased relevance to policymakers. For instance, Alberti & Waddell (2000) extend traditional urban simulation models by incorporating fine-graned, spatial data, micro-simulation techniques, and feedback loops between land conversion and environmental stressors. The effect of this model is to challenge static equilibrium assumptions and offer a more dynamic framework for urban sustainability. Similarly, Xu and Coors (2012) and Mercure et. al. (2016) both underscore the limitations of equilibrium-based environmental models – advocating for approaches that capture agent heterogeneity, path dependency, and non-linear interactions between social, economic, and ecological factors.

Different application areas have pushed scholars' to adopt wide ranging methodological frameworks and spatial temporal scales. Reinhart et. al. (2013) presents the Urban Modeling Interface (UMI), which focuses on building-level energy use, daylighting, and walkability in urban neighborhoods. A distinct feature of this type of research is very detailed, building level, modeling informed by various sources of data, which can then be aggregated to city-level performance measures, but also can inform individualized recommendations, e.g. on selecting buildings that benefit from energy retrofits. Al-Darwish et al. (2018) and Liu et al. (2021) employ cellular automata techniques – the latter enhanced by machine learning – to simulate urban expansion at high spatial resolutions. Lu et al, (2018) adopts an agent-based modeling approach to evaluate the potential impacts of shared autonomous taxis, focusing on individual commuter behavior and the resulting urban mobility patterns. Ma et al (2018) utilize a dynamic optimization framework to balance economic growth with atmospheric pollution control – emphasizing the role of clean energy policies and industrial restructuring. Leao, Bishop, and Evans (2001) focus on waste management and landfill site planning, where the interplay between urban expansion and waste generation is studied.

Overall, studies in this group are heterogeneous as they fit their modeling approach to the problems at hand. Nevertheless, their convergence lies in the shared recognition that urban systems are inherently dynamic and require integrative modeling frameworks to effectively capture environmental constraints. Moreover, a focus on detailed complexity and integration with GIS data, sometimes at the expense of incorporating feedback complexity, may be a noteworthy feature of this literature. The role of data in many of these models is more as 'input' than for 'calibrating' model parameters. In fact, detailed complexity and resulting computational costs may limit numbers of simulations and thus calibration options. So despite the salient role of data in this area of modeling, the correspondence of the results with empirical regularities may not be as reliable as modeling frameworks that explicitly fit models to historical trajectories.

# Insights Across Modeling Methods

The modeling methods adopted in the wide literature we reviewed are unified in attempting to account for interdependence among different sectors of urban systems and use of simulation to forecast the impacts of different interventions. Yet, the methods vary notably on a few dimensions. First, the boundary of models, i.e. the range of feedbacks and sectors considered, vary significantly. Some may focus on a single sector (e.g. travel demand) whereas others may include a couple other interacting sectors (e.g. households, businesses, and buildings; sometimes augmented by transportation). Fewer models go beyond this to also include interactions of those with transportation, infrastructure, education, crime, or environmental factors. This highlights a clear direction for future development, as the ripple effects of urban policies extend well beyond the core of business, household, buildings, and transporation, impacting many additional areas. Nevertheless, modelers should be wary of 'modeling the system' syndrome, a common pitfall when mechanisms are added to a model just because they "exist" in reality, not because they are relevant for the problem at hand.

Second, models in these literatures vary significantly in their level of aggregation. Contemporary models may span aggregate ones, with a handful of household, business, or building types, to very detailed models that explicitly represent each household, each business, or each building. The implications of such choices may be large. More detailed models may allow for capturing very specific policies, enable the study of emergent phenomenon that is harder to identify ex-ante, and provide additional face validity with some stakeholders who may be reassured by seeing those details. These benefits come at a cost: models in this domain are orders of magnitude slower to run compared to the aggregate alternatives focusing on similar mechanisms. Thus detailed sensitivity analysis and rigorous calibration may be much harder. Detailed complexity also obscures the structure-behavior link in models, making it harder to gain clear insights that help stakeholders align their mental models with important mechanisms in practice. This introduces the risk of black-box models that should be trusted or discarded, rather than tools for building insight and educating decision-makers.

A third dimension is the relationship with data. Here a useful distinction can be made between 'input' data, informing model structure and parameters, and 'output' data used for comparing model outcomes against historical data. With the potential exception of urban economics models, most modeling work in this space puts more emphasis on input data than calibrating to output. This may partly reflect the engineering roots of some of the modeling work in this space where good models can be built based on first-principles, and partially due to feasibility and cost considerations for calibrating extremely detailed and computationally expensive models. To the extent that models reflect broader boundaries, where human decisions interact with the physics of the problem, first-principle modeling goes only so far, and empirical estimation and calibration may be indispensable if results of the model are to be trusted by wider stakeholders.

Finally, we see notable variance in the engagement of stakeholders in the modeling process. While not common, some streams of work have established methods for bringing stakeholders into the modeling process with the aim of both enhancing the realism and relevance of mechanisms in a model, and for increasing the chances that insights from the modeling process will be adopted by those in decision-making positions. We can see much room for leveraging this insight into a broader range of models, though the required investment in time and community building is not trivial and thus may be prioritized for cases where modeling is to inform actual policy (versus exploratory, or theory development work).

# Discussion

This paper provides a comprehensive review of various urban modeling approaches, highlighting their strengths, limitations, and potential for integration. When comparing methods, the fragmented nature of urban modeling traditions is striking. Each discipline – complexity science, system dynamics, urban economics, land use and transportation, and urban sustainability – has developed its own methodologies and tools that tend to focus on specific aspects while neglecting others, limiting the ability to capture the full interconnectivity of urban systems which may be needed for many policy applications.

The integration of these modeling approaches presents an opportunity to develop more comprehensive and holistic urban models. By combining the strengths of each tradition, researchers can create models that account for long-term dynamics, cross-sector policy interdependencies, and unintended consequences. For example, integrating system dynamics with urban economics can provide a more nuanced understanding of how economic policies influence urban growth and vice versa. Similarly, combining land use and transportation models with environmental modeling can help assess the impact of urban development on ecological sustainability.

The findings of this paper offer opportunities for integrating modeling work with the needs of urban policymakers. The review underscores the importance of adopting interdisciplinary modeling approaches to inform decision-making. Policymakers often intuit that urban systems are inherently complex and interconnected, and that interventions in one sector can have cascading effects throughout the system. However, to turn that intuition into practical guidance they need methods to quantify systems-based perspective that considers the long-term and cross-sectoral impacts of their decisions and help to identify potential trade-offs and synergies between different policy objectives. Effectively capturing those interactions, however, is not just about having them in model equations. They need to be quantified in empirically reliable ranges, so that the costs and benefits can inform policy. Therefore models that can help policy need significant empirical grounding. Moreover, even well-calibrated, broad-boundary models may be ineffectual in impacting policy when stakeholders see them as black-boxes that they can't trust. Incorporating mechanisms to engage decision makers, as well as marginalized stakeholders often missed in the analysis of costs and benefits, may be critical to get from quantitatively robust models to ones that have a real shot at impacting policy.

The paper highlights several areas where future research can advance the field of urban modeling. First, much learning can come from borrowing best practices across different modeling communities. From effective formalizations to standard modules, synergistic tools, and estimation methods, there is much to learn across groups. This requires collaboration between researchers from different disciplines and the development of frameworks that facilitate the integration of diverse methodologies. Second, the availability of high-quality data is crucial for the development and validation of urban models. There is increasing work in novel data collection methods, integrating diverse data sources, and developing techniques for calibrating models to ensure their accuracy and reliability. Third, current urban models often overlook the social, cultural, and political dynamics that influence urban development. Future research should incorporate these factors to provide a more realistic understanding of urban systems and the challenges of change. This includes integrating qualitative data and lived experiences to capture the nuances of human behavior and decision-making as well as gaming and multi-stakeholder decision making challenges in the context of actual governance systems. Fourth, urban models can be valuable tools for scenario analysis and policy evaluation. Future research should focus on developing models that can simulate different policy scenarios and assess their long-term impacts on urban systems. This can help policymakers identify the most effective strategies for achieving sustainable urban development. Fifth, methods for making models more interpretable and understandable would be critical for bridging the gap between stakeholders' mental models and the complexity of emerging models. Finally, as cities face increasing challenges from climate change, future research should focus on developing models that assess the resilience of urban systems to environmental shocks. This includes integrating climate projections, assessing the vulnerability of urban infrastructure, and identifying strategies for enhancing urban resilience.

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# Appendix A - Complexity Science

| **Article summary and primary question** | **Unit of analysis, level of aggregation, and empirical grounding** | **Primary phenomenon modeled and conclusion** | **Practical connections** |
|---|---|---|---|
| **Barner et al. (2017)** propose a novel way of measuring entropy in cities that emphasizes multi-scale spatial structure rather than simply evenness or randomness in geographic space. Their central question: if we treat each place's state as including its own land use plus the land uses of surrounding zones (at several scales), how does entropy reveal the likelihood—and the emerging structure—of different urban patterns? | Their approach partitions a city into spatial cells (or "places"), each with a land-use category (or distribution). For each cell, they measure not just its immediate use, but also the aggregated usage patterns in concentric neighborhoods of different sizes (e.g., 50 m, 150 m, etc.). In this way, the "state" of a cell is a multi-scale matrix of land-use proportions. They apply this method to West London (1875–2005), using building-level maps aggregated into three land-use categories. | Authors interpret entropy in a statistical mechanics sense: a city pattern has higher entropy if there are more distinct ways for the same macro outcome to arise under multi-scale interdependencies. Their key finding is that more "complex" urban layouts—those with multiple local patterns, mixing, and polycentric sprawl—exhibit higher multi-scale entropy than simpler or more uniformly random distributions. In the West London case, the actual historic growth shows systematically higher multi-scale entropy than random or simply compact/segregated allocations, suggesting that real urban evolution tends toward these rich, multifaceted patterns. | By embedding urban patterns in a multi-scale statistical framework, planners and modelers can better grasp why cities often become multi-centric and "messy." In effect, polycentric sprawl may arise simply because there are far more micro-level combinations that produce these flexible, diverse configurations. For planning, this work suggests that embracing multiple scales and acknowledging interdependencies leads to more robust predictions of a city's probable form. It can also guide strategies for dealing with uncertainty—if we want to design urban fabric adaptable to changing uses, higher multi-scale entropy may be beneficial, reflecting greater "built-in" choice and resilience. |
| **Bettencourt et al. (2007)** investigate how a wide range of urban characteristics depend on the population of a city. They observe consistent | Authors treat the city as the key unit of analysis, defining it by functional economic and commuting boundaries rather than strictly political ones. They | The paper models how resource use, economic outputs, and social activities in cities change with increasing population. Bettencourt et al conclude that | These findings provide a quantitative lens through which policymakers can understand the benefits and challenges of larger cities. On one hand, cities can exploit economies of |

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| power-law relationships ("scaling laws") across cities in different countries and time periods. The primary question they address is why certain urban indicators (e.g., wages, GDP, crime rates) systematically increase faster than population (superlinear scaling) while others (e.g., infrastructure networks) increase more slowly (sublinear scaling), and how these patterns reveal universal properties of urban life. | aggregate social, economic, and infrastructural metrics for entire urban systems, often using population size as the foundational variable. Their empirical grounding draws on large datasets from the United States, Europe, and China, encompassing dozens to hundreds of cities, ensuring that the observed scaling patterns are robust across diverse geographies and development levels. | while infrastructural metrics tend to display economies of scale (scaling sublinearly with population), socioeconomic variables linked to creativity, innovation, and wealth creation scale superlinearly, meaning they grow disproportionately with city size. This "faster-than-expected" growth in social outputs also drives an accelerated pace of life, reflecting the unique role of cities as hubs for interaction and knowledge spillovers. | scale to reduce per capita infrastructure costs; on the other, they must address potential drawbacks of superlinear growth, such as rising crime rates or housing costs. The research implies that sustainable urban growth requires continual adaptation and innovation cycles—ideas particularly relevant to managing environmental impacts and ensuring that increasing population density aligns with improvements in well-being and resource efficiency. |
| **Bettencourt et al. (2010)** examine how measures such as wealth (income and GDP), innovation (patent production), and crime systematically scale with city population—then investigate why certain cities deviate from these universal "baseline" patterns. Their core question: how do we best measure a city's true performance once the typical (nonlinear) effects of size are accounted for? | The analysis targets U.S. Metropolitan Statistical Areas (MSAs). Their dataset spans hundreds of MSAs over multiple decades, capturing economic indicators (income, GMP), innovation (patents), and crime. By fitting power-law (scaling) relationships of these indicators to population size, they show that size alone explains 65–97% of the variation—leaving a smaller portion for city-specific dynamics. | Authors model how major urban indicators change with population and define local deviations—SAMIs—as a universal way to quantify whether a given city's wealth, patenting, or crime is above or below its predicted scaling curve. A key conclusion is that these local residuals are not random but exhibit persistent long-term patterns, often stable for decades. Thus, historically higher-performing cities generally remain so, while underperforming ones sustain that status over time, highlighting strong path dependence in urban evolution. | By distinguishing systematic effects of city size from true local performance, policymakers can compare "apples to apples," especially among urban areas of different scales. This method clarifies which cities are genuinely exceptional (positively or negatively), helps set more realistic policy targets, and facilitates cross-city learning even when they are not geographic neighbors. It also underscores how significant urban change (whether improving incomes or combating crime) typically requires sustained, long-term interventions that can shift a city's local trajectory over decades rather than years. |

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| In “The Organization of Urban Systems,” **Bretagnolle, Pumain, and Vacchiani-Marcuzzo (2009)** examine how cities evolve and interact within larger systems, using a complexity perspective. The central question posed: How and why do city systems exhibit stable yet evolving hierarchical structures, and what factors drive their long-term patterns of expansion, interaction, and differentiation? | The city considered within broader systems of cities is the primary unit of analysis. Empirically, they use historical population databases and census data from multiple national contexts (such as Europe, India, the United States, and South Africa) spanning centuries, enabling them to compare how different trajectories of urbanization shape city system morphology and hierarchy. An evolutionary, dynamic modeling framework is used, drawing on Gibrat-like random growth processes to demonstrate how city sizes change through endogenous interactions (competition, innovation adoption, and network effects) without converging to a single fixed equilibrium. | Authors model the evolutionary growth of urban systems, focusing on phenomena such as rank-size distributions, spatial diffusion of innovations, and hierarchical differentiation among cities. They conclude that once established, systems of cities exhibit a self-reinforcing hierarchy: the largest cities tend to adopt innovations early and grow more rapidly, further consolidating their advantage. These hierarchical patterns reflect deep historical contingencies—such as modes of colonization or transportation advances—that leave enduring marks on each city system’s shape and growth. | From a practical standpoint, this research informs urban planners about the long-term forces that produce uneven growth and concentration in certain cities. By recognizing the ways transport innovations, political shifts, and economic changes alter city dynamics, stakeholders can more effectively forecast and shape urban development. |
| **Hong et al. (2020)** ask if cities follow a universal economic pathway as they grow, what mechanisms drive the transition from manual labor to innovation-based economies, and how city size correlates with economic structure. | Analyzes employment data from over 100 million U.S. workers spanning 350 cities between 1998 and 2013. Primarily examines data from 350 US MSAs. Nineteen broad industry sectors were considered, and categorized using the North American Industry Classification System (NAICS). Analytical framework guided by scaling laws. Employs statistical models to compare cross-sectional and longitudinal data on employment and population changes. | City size (population) determines economic and industrial structure. Cities follow a universal pathway of economic evolution resembling biological growth patterns coined Urban Recapitulation by authors. At ~1.2 million, cities transition from a small cities to large, innovation-based economies. | Provides a framework for urban policymakers to anticipate and manage transitions to innovation-based economies. Industries heavily reliant on local consumption exhibit stronger adherence to scaling laws and urban recapitulation. |

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| | Formulas for recapitulation scope and decomposition of employment growth. Lead-follow matrix to analyze the influence between cities of different sizes. Validation. | | |
| **Mora et al. (2021)** examine how urban population size correlates with both the absolute incomes earned at different points in the income distribution and with overall income inequality across U.S. cities. Previous urban scaling work showed that aggregated outputs (like total income) can rise faster than linearly with population, but this study asks which income groups truly benefit from these "superlinear" gains. In other words, the central question is how population size influences the distribution of these benefits—and whether poorer deciles see the same gains from larger urban scale as richer deciles. | Authors employ MSAs and use 2015 American Community Survey data to estimate each city's individual-level income distribution by summing up tract-level, Gaussian-modeled incomes. The analysis focuses on deciles (e.g., bottom 10%, second 10%, etc.) to see how total income in each decile scales with city population. This decile-based approach is key, as it separates overall gains in average income from shifts in how incomes are spread out. They also incorporate local housing costs to adjust incomes for affordability differences across U.S. cities. | By examining the scaling of income in each decile, the authors show that the highest decile scales with the most pronounced superlinearity (about 1.15), whereas the bottom decile scales roughly linearly (an exponent near 1.0). In other words, the richest 10% gain disproportionate benefits as city population grows, while the poorest 10% see no additional advantage versus a simple one-to-one scaling of population. Once housing costs are considered, the gaps are even more stark, showing larger cities to be less affordable—particularly for low-income residents. A closer look at full income distributions (moments like variance and skewness) suggests that not only do bigger cities have higher average incomes, but they also have systematically wider and heavier-tailed income distributions, leading to greater inequality. | These findings complicate the frequent narrative that all city-dwellers automatically benefit from the well-documented "superlinear" boost in total productivity. Policymakers aiming to leverage large-city growth must consider that this rising tide does not lift all boats equally. In particular, richer groups benefit disproportionately, while the relative condition of poorer groups can remain stagnant or even worsen once housing costs are factored in. This nuanced view of urban inequality can inform housing and social policies that target affordability and inclusive economic development. More broadly, it highlights the need to embed heterogeneous interactions in urban scaling theories—since the superlinear gains seem concentrated at the upper end of the income ladder, understanding and mitigating this skew is critical for equitable policy-making in growing urban centers. |
| **Raimbault & Pumain (2020)** advocate for an approach to | Examines systems of cities rather than individual cities and seeks to | Urban systems evolve through co-evolutionary processes, | Urban complexity is best understood through an evolutionary framework |

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| urban planning that combines empirical data, mathematical modeling, and computational simulations, asking how urban complexity can be understood using evolutionary theory. The paper also looks into how spatial interactions and path dependence shape urban hierarchies, and whether simulation models can capture urban growth mechanisms across different scales. | capture urban growth through aggregate population data, transportation networks, and economic linkages. Builds on complexity theory and evolutionary urban science, arguing that urban systems should be understood as co-evolving networks. Authors use two datasets: GeoDiverCity and Global Human Settlement Layer (GHSL). | where cities are interdependent units that grow in relation to each other. Spatial interactions, transportation networks, and hierarchical innovation diffusion shape urban realities, meaning the flow of people, goods, and information dictates city growth. Cities compete and collaborate through these networks. | that integrates spatial interactions, infrastructure networks, and innovation diffusion. Advocates for computational models as essential tools for testing urban theories to help researchers and policymakers better predict and manage urban transformations. |
| **Xu and Harriss (2010)** examine the rank-size distribution of cities focusing on how spatial and temporal autocorrelation affects city growth. The authors develop a methodology to better simulate urban growth dynamics and improve understanding of regional city systems. The central question: "How do spatial and temporal autocorrelations influence city rank-size distribution, and how can they be integrated into urban growth models?" | The unit of analysis is individual cities in Texas. The study is conducted at the regional level, analyzing urban growth patterns over time. While each city is treated as a distinct entity, the model accounts for interdependencies among cities by incorporating spatial proximity and historical growth trends. | Authors find that cities do not grow in isolation—nearby cities exhibit similar growth rates, and past growth trends influence future development. The findings reveal that Texas cities deviate from Zipf's Law, particularly in smaller cities, where traditional models underestimate their persistence and development patterns. The authors conclude that accounting for spatial and temporal interdependencies improves city rank-size simulations and offers a more realistic representation of urban growth dynamics. | Findings suggest that urban policy and planning should consider the interconnected nature of city growth. Regional planning strategies should acknowledge that nearby cities influence each other's development, and growth projections should incorporate historical trends rather than assuming independence. Infrastructure investments and economic policies should account for spillover effects between cities, ensuring that interventions support broader regional stability rather than isolated urban centers. The study provides a methodological framework for improving city growth simulations, which can be used by policymakers, economists, and urban planners to enhance forecasting accuracy and strategic planning. |
| **Yang, Ko, and Cho (2024)** introduce the "Oscillation and Wave Framework" to examine | The unit of analysis is urban economic systems with a focus on individual workers and firms | The study models the interaction between economic oscillations (fluctuations in | Policymakers should integrate economic policies with urban planning by managing congestion more |

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| the interplay between economic policy and urban planning. The study identifies critical congestion thresholds that shape urban clustering and sprawl. The central question: “How do economic oscillations and spatial waves interact in shaping urban development, and how can they inform sustainable urban planning and economic policy?” | within a simulated city environment. The study aggregates data at multiple levels—individual, sectoral, and citywide—modeling the effects of economic policies and spatial population dynamics on urban form. Authors use agent-based modeling to simulate urban economic and spatial dynamics. The model consists of a 50×50 grid with 2,500 spatial units and tracks the movements of 150 worker agents across traditional, innovative, and service industries. Sensitivity analyses and time-series simulations provide further validation of the framework’s robustness. | workforce size due to economic policies) and spatial waves (urban expansion and contraction patterns). The results reveal that adjusting congestion parameters leads to distinct urban forms—high-density clustering at low congestion levels and sprawling urban expansion at high congestion levels. A critical congestion threshold is identified as the tipping point between stable urban aggregation and excessive dispersion. | strategically. Investments in infrastructure, land-use regulation adjustments, and targeted incentives for industrial location planning can enhance urban efficiency and mitigate negative congestion effects. |

# Appendix B - System Dynamics

| Topic | Article summary and primary question | Unit of analysis, level of aggregation, and empirical grounding | Primary phenomenon modeled and conclusion | Practical connections |
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| Environment | **Cheng, Chang, and Lu (2015)** analyze the impact of urban transportation management policies on energy consumption and CO2 emissions using a system dynamics model. The study focuses on Kaohsiung City, Taiwan, simulating a 30-year timeframe (1995–2025) to evaluate different policy interventions, including fuel taxation, motorcycle parking management, and free bus services. The study seeks to determine the most effective strategies for reducing vehicular fuel consumption and mitigating CO2 emissions. The primary research question is: How can system dynamics modeling inform urban transportation policies to reduce energy consumption and carbon emissions in a rapidly developing city? | The unit of analysis is the urban transportation system of Kaohsiung City, incorporating multiple subsystems such as population dynamics, economic growth, vehicle ownership, and energy use. The model is highly aggregated, representing citywide trends rather than individual travel behaviors. Empirical data from official government sources, including Taiwan's Statistical Abstract of Transportation and Communications and the Taiwan Emissions Database System, provide parameter values for calibration. However, the study primarily relies on simulation rather than direct validation against historical observations. | Authors model the relationship between urban transportation policies, vehicle usage, and energy-related CO2 emissions. It finds that both fuel taxation and motorcycle parking management effectively curb vehicle ownership growth, fuel consumption, and emissions. While free bus services increase public transit ridership, they have a minimal impact on reducing private vehicle use. A combined policy approach, integrating all three interventions, yields the most significant reductions in emissions and fuel demand. The authors conclude that system dynamics modeling is a valuable tool for testing policy effectiveness and informing sustainable transportation planning. | The importance of economic incentives, such as fuel taxation, in influencing travel behavior and vehicle ownership are highlighted in this research. The effectiveness of parking management policies suggests that urban design and regulatory measures can complement financial policies to shape sustainable mobility patterns. The proposed system dynamics approach can be adapted to other cities, particularly those with high vehicle dependency and growing energy concerns, to assess the long-term impact of transportation policies. |

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| Environment | **Ghasemi, Saghafian, and Golian (2017)** apply a system dynamics (SD) model to analyze the long-term sustainability of Tehran's urban water system, with a specific focus on groundwater resources. The study investigates the interactions between population growth, water demand, and water supply, considering the impacts of climate variability, urbanization, and water management policies. The authors ask, how can system dynamics modeling support sustainable urban water management, particularly in maintaining groundwater balance in Tehran's rapidly growing metropolitan area? | The model operates at a city-wide scale, incorporating major water sources, including reservoirs, rivers, and aquifers, while also accounting for consumption patterns across domestic, industrial, and agricultural sectors. Empirical grounding is established through data from Tehran's water utility reports, meteorological records, hydrological studies, and urban planning documents. The model undergoes calibration and validation using historical population trends, surface runoff measurements, and groundwater level changes, achieving an $R^2$ value of 0.99 for population growth and 0.83 for groundwater levels. | Authors model the interactions between water demand, supply, and conservation strategies, highlighting the critical role of groundwater in meeting Tehran's water needs. Results indicate that without intervention, water shortages will worsen due to rising demand and decreasing groundwater recharge, particularly as wastewater collection infrastructure expands. Scenario analysis reveals that inter-basin water transfers and leakage reduction could decrease water shortages by 32.2%, while widespread adoption of water-saving technologies could further reduce shortages by 31%. The authors conclude that a combined approach—integrating structural measures like water transfers with non-structural solutions such as demand management—is essential for sustainable water resource planning in Tehran. | The study underscores the importance of holistic water management, advocating for a combination of infrastructure investment, conservation policies, and public engagement. Specific recommendations include accelerating leakage reduction programs, promoting water-efficient household appliances, and implementing policies to regulate groundwater extraction. The system dynamics model serves as a strategic planning tool, allowing decision-makers to evaluate long-term water sustainability under various policy scenarios, ensuring resilience against climate variability and rapid urban growth. |
| Environment | **Gober et al. (2011)** introduce WaterSim, a system dynamics-based | The study focuses on Phoenix's regional water system, aggregating water | The model examines the balance between water supply, demand, and | The study provides a decision-support framework for |

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| | simulation model designed to explore the interplay between climate change, population growth, and policy decisions in shaping Phoenix's long-term water sustainability. The model integrates surface and groundwater supply, demand from municipal, industrial, and agricultural sectors, and policy levers affecting resource allocation. This paper asks how can simulation modeling inform policy decisions to ensure long-term water sustainability in Phoenix, Arizona, amid climate uncertainty and rapid urbanization. | supply from surface sources (Colorado River, Salt-Verde River systems) and groundwater reserves, alongside demand from urban, industrial, and agricultural users. The model operates at a metropolitan scale, integrating physical hydrology with socioeconomic drivers such as land use and demographic change. Empirical data sources include historical hydrological records, census population projections, and Arizona Department of Water Resources reports. The model undergoes sensitivity testing and history matching against past reservoir levels and municipal water consumption, confirming its validity in replicating historical trends. | sustainability under different policy and climate scenarios. Key findings reveal that maintaining current water consumption patterns while experiencing climate-driven reductions in surface water would lead to unsustainable groundwater depletion. A business-as-usual approach results in severe groundwater overdraft, reaching 46 billion cubic meters by 2030 under drought conditions. However, implementing demand-side measures, such as stricter water use regulations and high-density urban development, could significantly reduce overdraft while preserving urban growth. The study concludes that Phoenix's long-term water sustainability hinges on integrating conservation policies with adaptive, climate-responsive planning. | policymakers, demonstrating how scenario-based planning can guide urban water management strategies. The model's interactive design enables stakeholders to experiment with different policy interventions, reinforcing its role as a participatory planning tool. Key recommendations include restricting groundwater overdraft, incentivizing water-efficient urban development, and exploring alternative water sources to mitigate the risks of prolonged drought and population-driven demand increases. |
| Environment | This article by **Harich (2010)** argues that our collective failure to achieve global environmental sustainability stems primarily from systemic | The analysis focuses on the interaction between social, political, and economic structures—particularly how forces favoring | Harich's central phenomenon is the feedback loop of "change resistance," in which powerful interests and systemic structures adapt | The article suggests that effective action should focus on weakening the forces that resist policy changes, particularly by reducing deceptive or |

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| | "change resistance," rather than from simply not knowing the right practices. Despite decades of effort to promote proper policies and technologies, societies continue to resist adopting them at scale. The paper asks why, despite understanding many of the technical and policy solutions, we have not effectively solved the environmental sustainability problem. | change clash with forces resisting change. It uses a high-level, qualitative system dynamics model to represent these structures. Empirical observations (e.g., past environmental movements, corporate influence, and policy inertia) provide real-world grounding for the model's assumptions and support its conclusions about systemic obstacles. | to block or dilute proposed solutions. The key conclusion is that overcoming this resistance must come before—or at least alongside—implementing technical fixes. In other words, unless we address the deeper structural barriers that oppose change, efforts to properly couple the human economy with the environment will continue to fail. | manipulative political influence. It proposes redesigning institutions (like corporations) so their goals align with societal well-being. In doing so, activists, policymakers, and researchers would be better able to transform the system's "implicit goals" and break through the entrenched resistance that has long stifled environmental solutions. |
| Environment | **Wu and Ning (2018)** develop a system dynamics (SD) and geographic information system (GIS) model to assess the interactions between the economy, environment, and energy (3E system) in Beijing. Their primary question is how policy interventions influence the long-term sustainability of urban economic growth, environmental protection, and energy consumption. The study explores four policy scenarios—current, technology-driven, environment-focused, and energy-focused—to analyze their long-term | The model operates at two levels of analysis: temporal trends using system dynamics and spatial patterns using GIS. The SD model consists of eight interconnected subsystems, including GDP growth, technology investment, capital input, renewable and nonrenewable resources, and pollution emissions ($SO_2$, COD, and solid waste). The GIS model is used to spatially distribute simulation results across Beijing's 16 districts and 328 streets/towns, analyzing localized impacts of urban policies. Empirical grounding comes from | The study models the dynamic feedback loops between economic growth, energy use, and environmental degradation under different policy scenarios. Findings indicate that the current scenario is unsustainable, leading to high pollution and energy depletion. The technology scenario supports economic growth but does not fully mitigate environmental damage. The environment scenario achieves long-term stability by balancing economic growth with ecological conservation, while the energy scenario promotes resource efficiency but | This work emphasizes that integrating environmental and energy policies into economic planning is crucial for long-term sustainability. By spatially mapping the impacts of policies, the findings highlight the importance of district-level policy customization, ensuring that high-pollution and high-energy-consumption areas receive targeted interventions. The authors recommend a multi-pronged policy approach that incorporates technology, regulatory frameworks, and resource-efficient strategies to achieve a |

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| | implications on economic and environmental stability. By integrating SD for temporal analysis and GIS for spatial analysis, the authors provide a dynamic assessment of how urban policies shape economic growth, pollution levels, and energy resource consumption. | Beijing Statistical Yearbooks (2000–2015) and government data, ensuring that parameter values and scenario assumptions align with real-world economic and environmental conditions. | limits GDP growth. The authors conclude that no single policy approach is sufficient for sustainable urban development, and that a combined strategy integrating technology, environmental protection, and energy efficiency is optimal. | balanced and sustainable urban future. |
| Land Use & Transportation | **Chang and Ko (2014)** propose a novel approach to land use planning that integrates dynamic multi-objective programming (DMOP) with system dynamics modeling. The paper highlights the challenges of balancing economic, environmental, and social objectives in urban land use planning, particularly in the face of uncertainty and dynamic system changes. The study introduces an interactive dynamic multi-objective programming (IDMOP) model, which allows decision-makers to iteratively refine land use strategies based on evolving system states. The primary research question: How can an integrated dynamic | The unit of analysis in this study is an urban land use system, with a specific focus on optimizing spatial allocations based on multi-objective trade-offs. The model operates at a city-district level, aggregating various land use categories such as residential, industrial, commercial, public, and reserved areas. Empirical grounding is provided through a case study of Cijin Island, Taiwan, where the model is applied to simulate land use changes over three planning periods (2011–2025). While real-world constraints and demographic data inform the model parameters, the study primarily relies on simulated outcomes rather than empirical validation | Dynamic interactions between land use decisions and urban development, emphasizing the trade-offs between economic growth, environmental sustainability, and social equity are investigated. The authors conclude that integrating system dynamics with multi-objective programming provides a more flexible and adaptive planning framework compared to traditional static optimization models. The approach allows for better accommodation of stakeholder preferences and dynamic environmental changes, leading to more balanced and sustainable land use decisions. | By incorporating iterative optimization and simulation, the IDMOP model provides a structured method for evaluating alternative land use policies in response to changing urban conditions. The case study demonstrates how this approach can inform real-world decision-making, particularly in rapidly evolving urban environments where competing objectives must be balanced. The model's ability to incorporate stakeholder preferences makes it a valuable tool for participatory planning processes, ensuring that diverse interests are reflected in final land use decisions. |

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| | multi-objective programming and system dynamics approach enhance decision-making in land use planning under conditions of uncertainty? | through historical comparisons. | | |
| Land Use & Transportation | **Cox et al. (2017)** explore the interplay between transit investment and compact redevelopment in North Carolina. Facing rapid urbanization and concerns about transportation infrastructure, policymakers are debating whether light rail alone is sufficient to promote economic and sustainable urban growth, or if it needs to be paired with high-density redevelopment. The study utilizes a system dynamics model to simulate various land use and transportation scenarios between 2000 and 2040. The authors examine two main research questions: What role does redevelopment play in capturing the socioeconomic benefits of transit infrastructure investment? and How do redevelopment and light-rail transit interact to | The model focuses on urban transportation and land use interactions within Durham and Orange counties, specifically examining transit-oriented development (TOD) and housing market dynamics. The analysis is conducted at two geographic scales: Tier 1 (½-mile radius zones surrounding proposed light rail stations) and Tier 2 (the broader metropolitan region). The model is highly aggregated – integrating economic, demographic, and land-use feedback loops. It relies on regional planning datasets, including historical and projected census data, land use records, and economic statistics, ensuring empirical grounding. While key parameters are validated against available data, the model is primarily a scenario-based exploration rather than a strictly empirical study. | Findings indicate that transit and redevelopment work synergistically—while light rail alone can stimulate localized economic activity, its benefits are constrained without parallel land use changes. When combined, the two strategies result in greater employment, higher transit ridership, and improved land use efficiency. However, the study also finds that this synergy exacerbates housing affordability challenges, as increased demand drives up property values and rental costs, disproportionately impacting lower-income residents. The authors conclude that policies such as affordable housing initiatives must accompany transit-oriented development to mitigate displacement risks. | The research has direct implications for urban planners and policymakers considering transit investments as a tool for economic revitalization. It underscores that simply building light rail infrastructure is insufficient to maximize urban development benefits—coordinated land use planning is necessary. However, without safeguards, such as affordability policies, these strategies risk worsening housing insecurity. |

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| | affect housing and transportation affordability? | | | |
| Environmental | **Feng, Chen, and Zhang (2013)** develop a system dynamics (SD) model to analyze urban energy consumption and $CO_2$ emissions in Beijing from 2005 to 2030. Their primary question is how urban energy demand and carbon emissions evolve over time under different economic growth and policy scenarios. The study highlights the interconnections between socioeconomic development, energy consumption, and carbon emissions, aiming to identify key drivers and mitigation strategies. The authors use Stella to construct a multi-sectoral SD model, integrating the socioeconomic, industrial, service, residential, transport, and agricultural sectors to simulate Beijing's energy and emissions trajectories. | The study operates at the city level, analyzing sector-specific energy consumption. The SD model aggregates energy use across six economic sectors, each modeled with sector-specific energy intensity, fuel mix, and demand drivers. Empirical grounding comes from historical energy use data (2005–2010), Beijing Statistical Yearbooks, China Energy Statistical Yearbooks, and government reports. The model calibrates historical trends and projects future scenarios based on economic growth rates, population changes, and energy transition policies. A sensitivity analysis is conducted to assess how changes in GDP growth, population, and service sector expansion impact future energy demand. | Authors model the evolution of Beijing's energy demand and $CO_2$ emissions, examining sectoral contributions, energy efficiency improvements, and the effects of shifting fuel sources. Findings indicate that total energy consumption in Beijing will rise from 55.99 Mtce (million tonnes coal equivalent) in 2005 to 114.30 Mtce by 2030, with the service sector surpassing industry as the dominant energy consumer. $CO_2$ emissions are projected to increase by 43% over the study period, with the transport sector emerging as a major contributor due to rapid vehicle growth. The study concludes that while Beijing's energy intensity will decline due to efficiency gains and a cleaner energy mix, absolute energy consumption and emissions will continue rising without stronger policy interventions. | This workenables policymakers to test alternative policy scenarios, demonstrating that transitioning from coal to natural gas and expanding the service economy can significantly reduce emissions. However, the findings highlight that structural changes alone will not be sufficient to curb long-term emissions growth—a combination of energy efficiency policies, population controls, and urban transport reforms is necessary. The study suggests that Beijing must adopt multi-pronged strategies, including stricter vehicle emissions standards, energy diversification, and carbon pricing mechanisms, to achieve sustainable urban energy transitions. |

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| Land Use & Transportation | **Fu, Wu, Che, and Yang (2017)** investigate how land-use changes influence net carbon emissions at the city level, using a coupled system dynamics (SD) and CLUE-S (Conversion of Land Use and its Effects at Small Regional Extent) model. The core research question: How do land-use changes affect city-level net carbon emissions, and what land-use strategies can help mitigate emissions in rapidly urbanizing areas like Shanghai? | The unit of analysis is the urban land-use system of Shanghai, with a focus on five major land-use categories: agricultural land, water bodies, ecological land, construction land, and other land. The model operates at a spatially explicit regional scale, incorporating both macro-level economic and demographic trends and localized land-use dynamics. Empirical grounding is established through historical land-use data, Shanghai's statistical records, and planning documents. The model is validated using historical data from 2000 to 2013, with a Monte Carlo simulation applied for sensitivity testing, demonstrating an error margin mostly below 5%. | The study models the relationship between land-use transitions and carbon emissions, capturing both carbon sources (e.g., construction land expansion) and sinks (e.g., ecological and agricultural land). It finds that Shanghai's carbon emissions are primarily driven by the conversion of agricultural land into construction land, while ecological land expansion slightly offsets emissions. Under a business-as-usual scenario, total net carbon emissions are projected to increase from 39.43 Mt in 2010 to 80.28 Mt in 2025, though at a declining growth rate. The study concludes that optimizing land-use allocation—through controlled urban expansion, farmland preservation, and enhanced green infrastructure—can slow emission growth and support long-term carbon reduction goals. | This research suggests two key strategies for reducing emissions: (1) optimizing land-use structures by limiting the unchecked expansion of construction land and increasing urban green spaces, and (2) promoting land-intensive compound use to improve efficiency while minimizing environmental impacts. Additionally, the findings highlight the importance of protecting sensitive ecological areas, particularly water source regions, and integrating carbon-conscious policies into Shanghai's long-term urban planning framework. The coupled SD-CLUE-S model also provides a transferable methodology for evaluating carbon emissions in other rapidly urbanizing cities. |
| Land Use & Transportation | **Güneralp, Reilly, and Seto (2012**) explore the effectiveness of a multiscalar urban | The study operates at two levels of aggregation: the regional level, where cities are analyzed as economic | The study models urban expansion and the interactions between regional economic growth | The research has strong implications for urban planning, regional policy-making, and |

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| | land-change model that integrates regional-scale system dynamics with local-scale spatial logit modeling. Their primary questions are: (1) Does coupling a regional system dynamics model with a local spatial logit model improve predictions of urban land change amounts compared to standalone models? and (2) Does this coupled model better predict spatial patterns of urban land change compared to a standalone spatial logit model? The study develops a Coupled System Dynamics Spatial Logit (CSDSL) model to examine urban growth in the Pearl River Delta, China, incorporating both regional economic dynamics and local biophysical and accessibility factors. The results show that the CSDSL model performs better than its standalone counterparts in predicting urban land change amounts and spatial complexity. | and population centers, and the local level, where urbanization is modeled at the 100m pixel scale. The regional-scale system dynamics model includes population, labor force, and economic sectors, simulating feedbacks among them. The local-scale spatial logit model predicts urban land conversion based on distance to urban centers, highways, topography, and economic activity. Empirical data include Landsat satellite imagery (1988–2004), economic indicators (GDP, capital investment), and field interviews with local decision-makers. The models are validated using historical land change data and separate time periods for calibration and testing. | and local land conversion patterns. Findings indicate that the CSDSL model improves accuracy by 15–18% in predicting the amount of urban land change compared to standalone spatial logit and system dynamics models. It also outperforms the standalone spatial logit model in capturing spatial complexity, but both models struggle to fully represent the fine-scale fragmentation of urban development. While the CSDSL model provides more realistic urban growth patterns, challenges remain in predicting highly dispersed development and speculative land investments. | land-use modeling. The CSDSL model offers a framework for integrating top-down regional policies with bottom-up local land conversion dynamics, making it useful for forecasting urban growth, evaluating zoning regulations, and assessing infrastructure investments. The study highlights the importance of multiscalar approaches in modeling urbanization dynamics, suggesting that policymakers should consider both economic drivers and localized land constraints when designing sustainable urban growth strategies. Future improvements in agent-based modeling and probabilistic forecasting could further enhance the accuracy of such integrated models. |
| Urban Dynamics | **Eskinasi, Rouwette, and Vennix (2009)** detail a | The model operates at a regional level, focusing on | Authors simulate how housing transformation and | By demonstrating the unintended consequences |

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| | group model-building initiative aimed at examining how new housing developments and urban renewal efforts shape the social housing market in Haaglanden, a highly urbanized region of the Netherlands. The project engages diverse stakeholders, including municipal officials and housing corporations, to foster a shared perspective on housing market dynamics and evaluate various policy scenarios. The system dynamics model is designed to capture the interactions between social housing supply, migration flows, and transformation processes. The study seeks to answer the key question: How do policies related to new construction and housing transformation impact the availability and allocation of social housing in Haaglanden? | the Haaglanden metropolitan area, which includes The Hague and surrounding municipalities. It aggregates the dynamics of the social housing market, modeling housing supply, demand, and allocation processes rather than individual household decisions. Empirical grounding comes from historical housing market data, migration statistics, and Dutch policy reports, ensuring that model assumptions align with real-world trends. However, certain parameters, such as migration multipliers, rely on expert estimates due to limited available data. | new construction policies affect social housing supply and accessibility. It finds that while urban renewal can improve long-term housing conditions, aggressive transformation policies may initially reduce the availability of social housing, exacerbating affordability issues. The study identifies critical delays in the housing market, showing that short-term reductions in transformation rates lead to long-term housing shortages. The authors conclude that balancing transformation with sufficient new construction is essential to maintaining a stable social housing market, and that housing allocation policies alone cannot resolve accessibility challenges. | of transformation policies, the study encourages decision-makers to consider the timing and sequencing of urban renewal efforts. The model also highlights the importance of greenfield development in sustaining social housing availability. Additionally, the findings support the use of system dynamics as a tool for collaborative decision-making, helping stakeholders align their strategies and test alternative policies before implementation. |
| Urban Dynamics | **Park et al. (2013)** explore the dynamics of urban development projects with a focus on self-sufficient city development. The study addresses the challenges of creating | The study focuses on new urban developments in South Korea, particularly self-sufficient cities planned to reduce dependency on Seoul's metropolitan core. The | Key findings indicate that business inflow and education welfare investment significantly enhance urban growth by improving employment opportunities and quality of | The research provides actionable insights for policymakers and urban planners designing self-sufficient cities. It highlights that while housing and service facility |

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| | cities that do not rely on external metropolitan areas for employment, services, and infrastructure. Using system dynamics modeling, the authors construct a causal loop diagram and simulation model to evaluate key policies influencing self-sufficient city growth. The central research question: What urban policies effectively promote self-sufficient city development, and how do their interactions shape long-term urban growth? | system dynamics model operates at a city-wide scale, integrating multiple urban subsystems—housing, business activity, service infrastructure, and population growth. Empirical data are drawn from Statistics Korea (2005) and previous urban development studies, but the model primarily functions as a policy-testing tool rather than a direct empirical validation of real-world cases. | life. In contrast, housing supply and service facility policies mainly accelerate the stabilization of urban populations but do not affect long-term growth. The study concludes that policies focusing on job creation and education infrastructure are more effective in fostering self-sufficiency than purely expanding physical infrastructure. Moreover, balancing positive and negative feedback loops in urban development is critical to avoiding unintended consequences such as overpopulation or economic stagnation. | investments help in the early phases of development, long-term success requires prioritizing economic activity and education services. The model serves as a decision-support tool, allowing urban planners to test policy interventions before implementation. The findings suggest that self-sufficient city policies should integrate demand-side incentives (e.g., attracting businesses) with supply-side investments (e.g., infrastructure and education) to create sustainable, economically independent urban centers. |
| Urban Dynamics | **Yeomans and Kozlova (2023)** explore the limitations of conventional system dynamics models in urban planning, particularly their lack of sensitivity analysis due to the time-dependent nature of outputs. The study introduces Simulation Decomposition (SimDec), an extension of Monte Carlo analysis, to improve the visualization of | Authors employ an abstract, simulated urban system based on the URBAN1 model as the unit of analysis. The model operates at an aggregated city-wide level, incorporating broad categories such as population, business structures, and housing stock. It does not rely on empirical case studies but instead uses Monte Carlo | The primary phenomenon modeled is urban system behavior under uncertainty, particularly how interdependent factors such as population dynamics, business growth, and housing availability interact over time. By applying SimDec, the study reveals that traditional sensitivity analysis methods fail to capture complex joint | By incorporating SimDec into system dynamics models, planners can better identify which factors have the most significant impact on urban outcomes and assess the range of possible future states under different policy scenarios. The study emphasizes that SimDec enhances transparency and understanding, making simulation-based insights |

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| | cause-effect relationships in urban models. By applying SimDec to a simplified version of Forrester's Urban Dynamics model (URBAN1), the authors investigate how input uncertainties, such as immigration and outmigration rates, impact urban system outcomes. The primary question addressed is: How can simulation decomposition enhance the sensitivity analysis of urban dynamics models to improve decision-making in urban planning? | simulations to explore theoretical dynamics. The study's grounding is methodological, demonstrating how SimDec enhances sensitivity analysis in system dynamics modeling rather than validating outcomes against real-world data. | effects, such as the intricate relationship between immigration, outmigration, and urban stagnation. The study concludes that SimDec provides a powerful tool for urban planners by uncovering previously hidden interactions in dynamic systems, making it easier to assess the impacts of different policy interventions. | more actionable for policymakers, especially in contexts where urban growth and decline are driven by multiple interrelated factors. |

# Appendix C - Urban Economies

| Article summary and primary question | Unit of analysis, level of aggregation, empirical grounding | Primary phenomenon modeled and conclusion | Practical connections |
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| **Albouy and Stuart (2014)** develop a neoclassical general-equilibrium model to explain the variation in urban population, density, and land supply across metropolitan areas. The central question addressed by authors revolves around how well the neoclassical model explains population and density variation across U.S. metropolitan areas, and how do local amenities shape these differences. | The study combines a theoretical model with empirical analysis using U.S. Census data and land-use regulations for 276 MSAs. It estimates structural relationships between urban wages, housing costs, and population density to infer local productivity and amenity values. | By linking these estimates to land supply elasticities and regulatory constraints, the model explains about half of the observed variation in urban population density and total population. Authos model urban location choices as a function of quality of life, productivity, and land availability. Cities with high quality of life attract more people, even at higher housing costs, while cities with strong trade productivity rely on labor mobility to sustain economic activity. Home productivity—linked to housing supply and non-tradable sectors—emerges as a dominant factor shaping urban density. The model suggests that excessive land-use regulations in high-productivity cities constrain growth, leading to inefficient population distributions. | The authors conclude that relaxing land-use constraints could increase national economic output by redistributing labor to more productive locations. Policymakers should consider reducing zoning restrictions in high-productivity cities to accommodate larger populations and enhance economic efficiency. The study also emphasizes the need to integrate land supply considerations into urban economic models, as regulatory constraints significantly affect housing affordability and city size. Federal tax policies further distort labor allocation by discouraging migration to high-wage areas. Reforming these policies could help balance regional economic development and improve national productivity. |
| **Behrens and Robert-Nicoud (2014)** develop a theoretical model that explains why larger cities tend to be both more productive and more unequal than smaller towns. Authors address the question, why | Authors aggregate firm productivity, income distributions, and labor market dynamics across multiple urban centers to model the systemic effects of agglomeration and selection. The | The interplay between urban size, productivity, and income inequality is modeled, finding that agglomeration economies attract firms and workers to large cities, where competitive selection | The role of firm selection in shaping urban wage structures is evident, implying that policies promoting entrepreneurship and firm competitiveness could influence wage distribution. |

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| are large cities more productive but also more unequal, and how do natural advantage, agglomeration economies, and firm selection contribute to these patterns?” | paper is primarily theoretical, employing a monopolistic competition framework extended to account for heterogeneous entrepreneurs and urban costs. While no new empirical data is introduced, the model is calibrated to match key stylized facts from prior empirical research on urban productivity, firm selection, and income inequality. | pressures favor the most productive firms. This results in higher average wages but also greater earnings inequality, as less productive firms struggle to survive. The model also predicts that cities with strong natural advantages (e.g., access to trade routes or key industries) experience faster growth and higher inequality. The authors conclude that urbanization is a self-reinforcing process where productivity gains and inequality evolve together, shaped by competition, selection, and economic geography. | Investments in infrastructure, education, and skill development can help ensure that a broader segment of the population benefits. Urban policymakers should focus on balancing the benefits of agglomeration economies with policies that mitigate rising inequality. |
| **Candau (2011)** explores whether urban agglomeration leads to socially optimal outcomes by incorporating land rents, commuting costs, and worker heterogeneity into a New Economic Geography model. The paper challenges the assumption that agglomeration is always beneficial by showing that it can generate excessive costs, particularly for low-skilled, immobile workers. Candau asks: “Under what conditions is agglomeration socially desirable, and when does dispersion lead to better welfare outcomes?” | The study focuses on two distinct worker groups—high-skilled mobile workers and low-skilled immobile workers—analyzing their location decisions within a two-region economy. At a higher level, it aggregates these effects to assess the overall efficiency of agglomeration versus dispersion. The model simulates equilibrium outcomes under different trade liberalization scenarios, allowing the author to compare the relative welfare of agglomeration and dispersion. Although no empirical data is used, the study builds on previous empirical findings regarding urban costs and migration patterns. | The author models how trade liberalization and urban costs influence equilibrium outcomes in a two-region economy. It finds that while agglomeration initially increases efficiency by concentrating economic activity, rising land rents and commuting costs eventually erode its benefits. The model predicts a “dispersion-agglomeration-dispersion” pattern as trade openness increases, meaning that agglomeration is not always the long-term outcome. Under some conditions, dispersion is found to be a Pareto-efficient equilibrium, making decentralization policies beneficial. The author concludes that agglomeration policies should not be taken for granted, as their | Results imply that trade policy and urban planning should be coordinated to ensure that spatial economic configurations maximize overall human welfare. Decentralization policies, such as infrastructure investment in secondary cities, can be beneficial if urban costs in large metropolitan areas outweigh agglomeration advantages. The study also highlights the need for land-use and transport policies that reduce commuting burdens, particularly for low-skilled workers who bear the highest costs of urban congestion. |

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| | | desirability depends on the balance between agglomeration benefits and urban costs. | |
| **Davis, Fisher, and Whited (2014)** examine the role of urban agglomeration in driving macroeconomic growth. This research challenges traditional growth models that omit urbanization dynamics, emphasizing the long-term macroeconomic consequences of density-driven productivity. Central question: “To what extent do local agglomeration economies contribute to aggregate economic growth?” | Authors employ a DSGE model calibrated with a mix of city-level panel data (22 U.S. cities, 1978–2009) and macroeconomic time series. It estimates the strength of agglomeration externalities using a generalized method of moments (GMM) approach, leveraging variation in land rents and TFP growth across cities. The instrumental variable strategy ensures that local productivity shocks do not bias the estimated effects of agglomeration. | The results indicate a statistically and economically significant link between urban density and national economic growth. Rising land prices lead firms to economize on space, increasing urban density and amplifying TFP growth. This process generates a self-reinforcing cycle where cities become more productive over time, contributing to higher aggregate consumption growth. The authors estimate that local agglomeration effects account for a 10.2% increase in per capita consumption growth, confirming the macroeconomic importance of urbanization. The study concludes that policymakers should recognize the long-term growth benefits of agglomeration and design policies that support rather than restrict urban expansion. | The findings suggest that urban land-use policies and infrastructure investments play a crucial role in national economic performance. Policymakers should focus on reducing land-use restrictions that artificially constrain city growth, as higher urban density fosters productivity and long-term economic expansion. Additionally, investment in infrastructure that supports urbanization—such as public transit and broadband connectivity—can enhance the positive spillover effects of agglomeration. Finally, the study underscores the need to integrate urban economics into macroeconomic policy discussions, as failing to account for the role of cities may lead to suboptimal national growth strategies. |
| **Farrokhi (2021)** develops a spatial equilibrium model that incorporates skill heterogeneity and agglomeration forces to examine the relationship between city size, wage inequality, and economic productivity. The central question posed: “How do skill-biased agglomeration forces shape wage inequality and labor | A structural spatial equilibrium model uses U.S. Census microdata from 283 metropolitan statistical areas (MSAs). Farrokhi analyzes individual workers and cities as units of observation, aggregating data at the metropolitan level. The model is calibrated to match observed wage distributions, employment | This work models the interaction between agglomeration economies, skill heterogeneity, and wage inequality in urban settings. Results indicate that local productivity spillovers account for approximately seventy percent of the relationship between city size and employment, while skill composition explains the | Findings highlight the importance of balancing agglomeration benefits with policies that address rising urban inequality. Policymakers should consider investments in infrastructure and housing supply to mitigate the negative externalities of excessive urban concentration. Additionally, place-based policies aimed at |

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| market outcomes across cities?” | shares, and housing market conditions. Instrumental variable techniques are used to address endogeneity concerns, leveraging housing supply elasticities and historical employment patterns to estimate agglomeration effects. | remaining thirty percent. | redistributing economic activity across regions should account for potential trade-offs between efficiency and equity. The study also underscores the need for education and workforce development policies that enhance skill mobility, ensuring that workers can access opportunities in both large and mid-sized cities. |
| **Gaubert (2018)** studies the spatial distribution of firms and the effects of place-based policies on firm sorting, agglomeration externalities, and aggregate productivity. Gaubert asks how heterogeneous firms sort across cities, and what are the implications for productivity, welfare, and place-based policies. | The study is conducted at multiple levels of aggregation, including firm-level productivity, sector-level characteristics, and city-size distributions. The study combines theoretical modeling with empirical estimation using French firm-level data. It structurally estimates the model by matching it to observed firm sorting patterns and productivity distributions. The analysis relies on indirect inference and Monte Carlo simulations to quantify the role of firm sorting in shaping agglomeration economies. | The paper develops a theoretical model to explain how heterogeneous firms sort across cities of different sizes and how these sorting patterns impact total factor productivity (TFP) and welfare. Larger, more productive firms benefit more from agglomeration economies and thus concentrate in bigger cities, reinforcing their initial productivity advantage. The model estimates that firm sorting explains nearly two-thirds of the productivity premium in large cities. The policy simulations show that easing local constraints on urban growth (e.g., relaxing zoning laws) significantly improves aggregate productivity and welfare, while policies that subsidize less productive cities distort firm location choices and lower overall economic efficiency. | Gaubert suggests that urban policy should focus on enabling city growth rather than subsidizing underdeveloped areas. Reducing regulatory constraints such as zoning restrictions or height limits can enhance urban agglomeration effects and improve economic productivity. |
| **Glaeser and Gottlieb (2009)** explore the role of agglomeration economies in shaping urban economic success, emphasizing | The analysis is conducted at the metropolitan level, with a focus on U.S. cities. The study aggregates data at the city and regional levels, | The paper models urban economic performance as the outcome of spatial equilibrium, where workers and firms respond | Authors suggest that urban policies should focus on fostering human capital development and reducing barriers to housing |

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| how city density drives productivity and wage growth. The study examines how different cities grow, why wages and living costs vary, and how policies influence urban outcomes. The central question posed: How do agglomeration economies shape urban economic success, and what factors determine the spatial distribution of wealth and productivity across cities? | considering labor markets, productivity differences, and housing prices to evaluate urban economic dynamics. Authors review prior empirical estimates of agglomeration economies and use spatial equilibrium models to assess how labor mobility, housing supply, and local amenities influence urban growth. | to productivity, amenities, and housing constraints. It finds that modern urban growth is primarily driven by knowledge spillovers rather than traditional manufacturing clusters. The authors conclude that skilled cities grow faster due to human capital accumulation and idea exchange, reinforcing wage disparities between high- and low-density regions. They argue that policies affecting housing supply and land use regulations significantly influence urban economic outcomes, with restrictive policies potentially exacerbating inequality. | supply to enable efficient city growth. Investments in education and infrastructure can enhance the benefits of agglomeration economies, while excessive zoning restrictions may hinder economic dynamism. The study also highlights the importance of considering spatial equilibrium effects in policy design, as interventions affecting wages or housing markets can have unintended consequences on migration and urban affordability. |
| **Hsieh and Moretti (2019)** quantify the impact of housing supply constraints on the spatial misallocation of labor across U.S. cities and estimate the aggregate economic costs. In this paper, authors answer how do housing supply constraints in high-productivity cities affect labor allocation and aggregate U.S. economic growth. | The analysis relies on a structural spatial equilibrium model and U.S. Census data covering 220 metropolitan areas from 1964 to 2009. The study aggregates labor market and housing data at the city level, examining how local regulations influence national economic outcomes. | Authors model how labor misallocation due to housing constraints impacts aggregate economic growth and worker welfare. The findings indicate that restrictive housing policies in high-productivity cities prevent labor from moving to the most economically efficient locations, leading to lower national output. The model estimates that easing land use restrictions in cities like New York and San Francisco could increase U.S. GDP by 3.7% and raise average annual earnings by $3,685. Counterfactual simulations assess how national output and worker welfare would change if restrictive cities relaxed their zoning laws to match the median U.S. city. | Policymakers should focus on reforming zoning laws and other regulatory barriers restricting housing supply in high-productivity cities. Increasing housing availability in these regions would improve labor mobility, enhance economic efficiency, and boost aggregate output. Also highlights the need for federal or state-level interventions since local governments have incentives to restrict development to protect incumbent homeowners' interests. Investments in transportation infrastructure could help mitigate misallocation by connecting lower-cost regions to high-productivity labor markets. |

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| | | The paper concludes that local land use policies create negative externalities at the national level, distorting labor markets and reducing overall economic welfare. | |
| **Rossi-Hansberg and Wright (2007)** develop a general equilibrium model to explain how urban structure evolves alongside economic growth. Their primary question: “How does the formation and evolution of cities reconcile urban increasing returns with balanced economic growth?” The study addresses the tension between local increasing returns from urban agglomeration and the need for constant aggregate returns to sustain balanced economic growth. | The study focuses on individual cities as the core units of analysis, aggregating them within a broader macroeconomic framework to assess national and regional urban distributions.<br>Primarily theoretical but aligns with observed city size distributions and urban productivity trends. Historical U.S. Census data and cross-country urban size distributions support their framework, demonstrating that city size dispersion is consistent with productivity shocks found in empirical studies. | Authors model urban growth as a dynamic process where cities form, expand, and decline in response to productivity shocks, infrastructure constraints, and commuting costs. The model explains why cities do not grow indefinitely—rising congestion and commuting costs balance agglomeration benefits, leading to an equilibrium city size. The findings suggest that endogenous city formation is essential for maintaining macroeconomic stability while allowing urban economies to harness increasing returns. The authors conclude that urban structure is a key determinant of balanced growth, shaping both economic efficiency and spatial distribution patterns over time. | Findings empahsize the need for policies that support efficient urban expansion and infrastructure investment. Governments should focus on reducing congestion and improving transportation networks to sustain the benefits of agglomeration. Additionally, land-use policies should allow for the flexible development of new cities and urban extensions, rather than enforcing rigid zoning restrictions that artificially limit growth. The findings also highlight the importance of regional planning strategies that accommodate productivity shocks and shifting economic activity, ensuring that urbanization supports long-term economic development. |

# Appendix D - Land Use & Transportation

| Article summary and primary question | Unit of analysis, level of aggregation, and empirical grounding | Primary phenomenon modeled and conclusion | Practical connections |
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| **Anas and Rhee (2006)** develop and simulate a spatial general equilibrium model to understand whether (and how) urban growth boundaries (UGBs) and congestion tolls can reduce excess urban sprawl. Their central question is whether imposing urban growth boundaries – which restricts the outward expansion of the city – can serve as a second-best alternative to congestion tolls in curbing excess land consumption and travel distances. They examine the welfare impacts and efficiency trade-offs of each policy under varying assumptions about urban structure and household preferences. | The model treats the entire metropolitan area as composed of multiple concentric zones (a “circular city” approach). Land in each zone can be used for roads, residences, or production, and workers can both reside and work in any zone. The city’s boundaries can be extended or tightened (via the “greenbelt”). Although the paper’s emphasis is theoretical and simulation-based, it draws on realistic parameter values for congested speeds, commuting times, and land use shares. The model simulates land and labor markets, as well as location choices of households/firms with a focus on how each policy changes densities, travel times, and welfare outcomes. | The phenomenon is urban sprawl: excess outward expansion due to unpriced congestion and road misallocation. Two policies are compared: 1) Congestion tolls (plus self-financing road allocation), which charge drivers the full social cost of their trips and thereby curtail excessive travel demand; and 2) Urban growth boundaries, which limit city radius and force more compact development.<br>The authors conclude that congestion tolls are far more efficient in cutting excessive travel distances (thus sprawl) while UGBs can cause large deadweight losses, particularly if they must be very stringent to match the same travel-time reduction as congestion pricing. If households also value the compactness/greenbelt per se, UGBs can become more beneficial, but tolls are still needed to reduce congestion properly. | The results underscore that although UGBs are popular for controlling sprawl, they can impose severe housing and rent distortions if used alone. Policymakers seeking to reduce suburban expansion while minimizing welfare losses should focus on pricing road use (e.g., congestion tolls, or close second-best instruments like targeted gasoline/parking taxes) because they internalize the true cost of travel. UGBs may still play a role if preserving peripheral open space is strongly valued, but they do not correct the traffic underpricing; thus, even with UGBs, some form of congestion pricing is key to avoiding large welfare losses. |
| **Daganzo (2007)** presents a macroscopic, aggregate modeling | Urban neighborhoods as a reservoir are the unit of analysis, | The study models gridlock formation and prevention using | This research has direct implications for urban traffic |

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| approach to understanding and mitigating urban gridlock. The study introduces the concept of neighborhood-level reservoirs, where traffic dynamics are modeled at a coarse scale rather than through microscopic simulations. The primary question is whether adaptive control strategies—which regulate vehicle accumulation at the neighborhood level—can effectively mitigate congestion without requiring detailed origin-destination (O-D) data or microscopic traffic models. The study develops a theoretical framework for single- and multi-reservoir systems, showing how macroscopic principles can be used to improve urban mobility. | with streets and intersections aggregated into macroscopic variables such as accumulation (number of vehicles) and trip completion rate. The study proposes that, under homogeneous congestion, aggregate traffic variables (e.g., flow, speed, and trip completion) can be modeled as functions of accumulation, independent of individual vehicle movements. Empirical grounding is provided through references to previous empirical findings, including freeway congestion dynamics, but the study itself is primarily theoretical and requires field validation. | macroscopic traffic variables. It demonstrates that if vehicle accumulation exceeds a critical threshold, positive feedback loops can cause congestion to self-reinforce, leading to gridlock. To prevent this, the study proposes adaptive control strategies that meter vehicle entry into neighborhoods, ensuring accumulation stays near the optimal level for maximizing throughput. For multi-reservoir systems (i.e., entire cities), the study suggests that traffic should be dynamically managed across neighborhoods to balance congestion and maintain high accessibility. The conclusion is that macroscopic traffic control can improve urban mobility without requiring detailed O-D forecasting. | management and congestion pricing policies. The study suggests that adaptive accumulation-based (AB) control could be implemented using traffic signals, pricing schemes, or perimeter control strategies, as seen in cities like Zurich and London. Additionally, it proposes that real-time monitoring of vehicle accumulation using sensors or GPS-equipped vehicles could allow cities to dynamically adjust traffic flows without complex predictive models. The approach is relevant for multi-modal transportation planning, as it could be extended to pedestrian, bicycle, and transit networks. |
| **Deal and Schunk (2004)** investigate the economic costs associated with urban land use transformation, particularly the impacts of urban sprawl. Their primary question examines how dynamic spatial modeling can be used to assess the fiscal consequences of different urban development patterns. The paper introduces the Land Use Evolution and Impact Assessment Model (LEAM), which integrates ecological and economic considerations to evaluate the costs of urban sprawl in Kane | The unit of analysis is land parcels represented in a high-resolution 30x30-meter grid within a raster-based GIS framework. The model operates at multiple levels of aggregation, capturing micro-level land use decisions while assessing macro-level economic and environmental impacts. The study is empirically grounded in real-world data from Kane County, Illinois, incorporating census data, economic indicators, land use records, and transportation infrastructure details. The authors use empirical | Models the spatial evolution of urban land use and its associated economic and social costs, particularly in relation to low-density sprawl versus higher-density development patterns. The LEAM framework simulates how different land use policies influence infrastructure costs, environmental degradation, and social disparities. The findings reveal that low-density sprawl significantly increases communal and societal costs, including transportation infrastructure, public utilities, environmental damage, | The LEAM model provides a tool for scenario-based planning, allowing decision-makers to test the fiscal and environmental impacts of various development strategies. By integrating economic and ecological considerations, the model helps municipalities identify sustainable growth policies that minimize long-term public expenditures while optimizing land use efficiency. The study reinforces the importance of spatial modeling in urban planning, particularly for evaluating the trade-offs between |

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| County, Illinois. By applying a simulation-based approach, the authors aim to provide policymakers with a tool for analyzing the trade-offs between low-density and high-density urban expansion. | validation techniques such as the Kappa statistic to compare modeled spatial patterns against observed land use changes. | and social inequities. The authors conclude that more compact development patterns lead to lower long-term costs and greater fiscal sustainability for municipalities, highlighting the need for land use policies that balance economic efficiency with environmental and social concerns. | short-term development incentives and long-term communal costs. |
| **Hammadi and Miller (2021)** present a new agent-based microsimulation approach for transportation impact assessment. The study critiques traditional transportation impact studies, which often rely on non-behavioral methods and proposes a dynamic, agent-based modeling (ABM) system that integrates land-use characteristics with transportation demand analysis. The key question the paper addresses is: “How can an agent-based microsimulation framework improve the estimation of transportation impacts of new developments at the district, city, and regional levels?” | The unit of analysis is individual travelers and households, with the model operating at a microscopic level, while aggregating results across district, city, and regional levels to assess broader transportation impacts. The model is implemented and tested using Waterfront Toronto’s Bayside Development Phase 2 as a case study, applying the TASHA-based GTAModel V4.1 ABM travel demand model system. The empirical validation includes comparisons with trip estimates from conventional traffic impact studies and the Institute of Transportation Engineers (ITE) Trip Generation Manual (TGM) rates. | The primary phenomenon modeled is the interaction between land-use development and travel behavior, specifically how different architectural designs and population compositions impact transportation demand. The study concludes that the agent-based TISP model provides a more detailed, behaviorally grounded, and scalable method for assessing transportation impacts, outperforming traditional trip generation models in accuracy and applicability. | The research has direct implications for urban planners and policymakers, offering a computationally efficient and flexible model that can be integrated into real-world urban planning and transportation impact assessments. The findings suggest that agent-based approaches can enhance urban transportation modeling by capturing multimodal travel behavior, land-use interactions, and spatial-temporal travel patterns, making it a valuable tool for sustainable urban development planning. |
| **Kryvobokov et al. (2013)** compare two land use–-transport interaction (LUTI) models: the static equilibrium model Pirandello and the dynamic disequilibrium model UrbanSim, focusing on their applicability for evaluating urban | The unit of analysis for Pirandello is aggregated zones, focusing on regional equilibrium across 361 statistical zones. UrbanSim operates at a finer level of spatial granularity, using 304 zones (arrondissements in Lyon and | Authors model the impact of an urban toll on land use and transportation, analyzing shifts in population density, housing prices, and income group relocation. Both models predict similar general trends: population and housing | The comparison highlights key trade-offs for policymakers and urban planners when choosing LUTI models for policy analysis. Pirandello is computationally simpler, requires less detailed data, and provides a stable |

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| policy scenarios. The primary question they explore is whether static and dynamic urban modeling frameworks can generate comparable empirical results despite their fundamental conceptual differences. They apply both models to simulate the long-term effects of implementing an urban toll in Lyon, France, examining population distribution, housing prices, and income segregation patterns. | municipalities outside). Both models use multinomial logit functions to model household and employment location choices, with Pirandello considering housing stock constraints and UrbanSim incorporating path dependency. The empirical grounding comes from calibration using historical population, employment, and real estate price data for Lyon, as well as back-casting simulations to validate model predictions. | prices increase in the central city (Lyon and Villeurbanne) while suburban areas see population decline. However, UrbanSim captures more pronounced short-term changes due to its dynamic approach, while Pirandello's equilibrium method smooths outcomes over time. A key divergence is the treatment of high-income households—Pirandello predicts more suburbanization, while UrbanSim suggests they remain in the city center. The study concludes that static and dynamic models can generate comparable policy-relevant insights, but dynamic models provide a more detailed temporal trajectory of urban changes. | equilibrium representation of urban development, making it useful for long-term strategic planning. UrbanSim, in contrast, captures annual fluctuations and path-dependent effects, making it more suitable for incremental policy evaluation and forecasting short- to medium-term urban transformations. The findings emphasize that both models can be valuable tools, depending on whether policymakers prioritize long-term equilibrium analysis or dynamic scenario testing. |
| **Li and Liu (2007)** develop an integrated multi-agent system (MAS) and cellular automata (CA) model to simulate residential development patterns in Guangzhou, China. The primary question is how to define agents' behaviors in a consistent manner for urban simulation, given that traditional CA models struggle to incorporate individual decision-making processes. By combining MAS with multicriteria evaluation (MCE) and Geographic Information Systems (GIS), the study provides a structured approach to agent-based land-use | The study operates at the grid-cell level, with 100m x 100m resolution, integrating GIS-based spatial layers such as land use, land prices, accessibility, public facilities, and environmental quality. Three types of agents—residents, property developers, and government planners—interact within a two-dimensional urban environment. Empirical grounding is provided by satellite imagery, remote sensing data, census statistics, and land-use plans. Model calibration relies on historical land-use transitions from | Authors model residential land development by capturing the interactions between residents, property developers, and government planners within a dynamic urban environment. Residents make location decisions based on factors such as income, household size, land price, accessibility, amenities, and proximity to schools. Property developers respond to demand and land prices, seeking to maximize profits while navigating government regulations on land conversion. Government agents regulate urban expansion based | The study has significant implications for urban planning, land-use policy, and sustainable development. The agent-based modeling approach allows policymakers to simulate how different regulations, pricing strategies, and infrastructure investments influence urban expansion. The integration of GIS, remote sensing, and behavioral modeling offers a practical framework for decision-making in rapidly urbanizing cities. Additionally, the study highlights data challenges, such as uncertainties in government |

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| modeling, incorporating economic, spatial, and policy-driven constraints. | 1995 to 2004 in Guangzhou, validated using logistic regression and sensitivity analysis. | on environmental policies and public demand, influencing which areas are approved for development. The results indicate that the integrated CA-MAS approach offers a more nuanced simulation of urban growth compared to traditional cellular automata models, as it incorporates individual decision-making rather than relying solely on neighborhood-based transition rules. The study concludes that multicriteria evaluation (MCE) is a useful method for defining agent preferences, allowing for more realistic and behaviorally grounded urban simulations. | decision-making and incomplete developer data, which must be addressed for future model improvements. |
| **Long, Mao, and Dang (2009)** develop and apply the Beijing Urban Development Model (BUDEM) to analyze urban growth and simulate future land-use patterns in Beijing. Their primary question is how cellular automata (CA) modeling can be used to study urban expansion dynamics and inform urban planning decisions. The study aims to capture the self-organizing nature of urban development and integrate spatial constraints, environmental policies, and planning goals into a predictive framework. The model is calibrated using historical urban growth data from 1986 to 2006, | The unit of analysis is grid cells (500mx500m) across Beijing's metropolitan area, covering 16,410 km². BUDEM integrates logistic regression, Monte Carlo simulation, and multi-criteria evaluation (MCE) to determine transition probabilities for land-use changes. Empirical grounding is based on remotely sensed land-use data, urban planning documents, and historical socio-economic datasets. The model incorporates spatial factors such as distance to roads, rivers, city centers, and administrative boundaries, alongside urban policy constraints. Historical validation is performed by | BUDEM models the transformation of non-urban land into urban built-up areas and evaluates the impact of policy constraints, environmental limitations, and market-driven development. The findings suggest that Beijing's urban growth is strongly influenced by planning regulations, transportation networks, and land suitability. The model predicts that by 2020, urban expansion will largely follow planned guidelines, but unregulated sprawl could emerge if policies are not strictly enforced. The 2049 projection highlights potential conflicts between urban expansion and | The study's practical implications extend to urban planners, policymakers, and researchers seeking to manage Beijing's rapid urbanization. BUDEM serves as a decision-support tool to assess the long-term effects of zoning policies, transportation investments, and environmental constraints on urban growth. By allowing planners to simulate different land-use scenarios, the model helps optimize spatial planning strategies, prevent excessive land conversion, and balance development with ecological sustainability. The findings reinforce the importance of integrating computational |

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| tested against observed patterns, and used to forecast Beijing's urban form for 2020 and 2049. | comparing simulated urban growth with actual development from 1986 to 2006. | environmental preservation, stressing the need for sustainable land-use policies. The study concludes that CA-based modeling provides a powerful framework for simulating urban futures, offering planners a tool for evaluating policy scenarios. | models into urban governance to support evidence-based decision-making. |
| **Pinto, Antunes, and Roca (2021)** propose an integrated cellular automata (CA) model that simultaneously simulates land use changes and transportation dynamics. Traditional CA models treat transportation variables as exogenous, meaning they are pre-determined and not affected by land-use shifts. The authors seek to answer whether endogenizing transportation accessibility within a CA model can provide a more realistic representation of land use-transport (LUT) interactions. Their model incorporates irregular cell structures and a variable neighborhood effect, allowing transport network changes to influence land use evolution dynamically. The study applies the model to the construction of a ring road in Coimbra, Portugal, assessing how new transport infrastructure affects urban expansion. | The model operates at the land parcel level, using irregular cellular units instead of standard raster-based grids. This approach ensures that cells reflect real-world spatial structures, such as census blocks, urban boundaries, and road networks. Accessibility is calculated dynamically based on travel times over a real road network, making it an endogenous variable rather than a static input. The study employs census data, employment statistics, municipal master plans, and transport network data to calibrate the model to Coimbra. The calibration process utilizes a particle swarm optimization (PSO) algorithm, which optimizes multiple parameters to improve model fit. | Authors simulate land use changes in response to transport infrastructure modifications, capturing feedback loops between accessibility and urban expansion. When applied to Coimbra, the model reveals that the construction of a ring road significantly alters urban growth patterns by increasing land-use intensity in areas with improved accessibility. The results demonstrate that neighborhood interactions and transport accessibility are more influential than zoning regulations in determining land-use changes. By integrating transport dynamics into the CA framework, the study bridges the gap between land-use simulation and transport planning, allowing for more holistic urban modeling. The findings confirm that LUT interactions are best understood when transportation variables are treated as co-evolving with land use rather than static constraints. | The study provides critical insights for urban planners, policymakers, and transportation engineers by demonstrating a methodology for simultaneously evaluating land use and transport policies. The model can support scenario-based planning, allowing decision-makers to test how different infrastructure investments (e.g., new highways, transit systems) affect urban development. By making accessibility an endogenous factor, the framework enables realistic forecasts of urban expansion, helping to anticipate issues like sprawl, congestion, and infrastructure demand. Additionally, the study suggests that optimization-based calibration techniques, such as particle swarm algorithms, can significantly enhance the accuracy and applicability of CA models in real-world urban planning contexts. |
| **Waddell (2011)** explores the | The unit of analysis varies from | The study models the | The findings have direct |

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| challenges of integrating land use and transportation modeling for urban planning, emphasizing how academic models like UrbanSim can be adapted for real-world decision-making. The primary question is how integrated models can bridge the gap between theoretical research and practical applications in policy-making, regional planning, and environmental sustainability. The paper highlights institutional barriers, data limitations, technical challenges, and the need for models to be transparent, flexible, and computationally efficient. | individual households, businesses, and developers to metropolitan-level systems. UrbanSim, the focal model in the study, operates at a micro-simulation level, tracking parcel-level land use changes, employment shifts, and transport accessibility. Empirical grounding is drawn from real-world applications in cities like Detroit, Honolulu, Houston, Phoenix, Seattle, and San Francisco, where UrbanSim has been deployed. The model's modular structure allows it to incorporate diverse data sources such as parcel records, transportation networks, and demographic trends. | interdependence of land use and transportation to improve regional planning. It finds that institutional fragmentation, conflicting stakeholder interests, and technical complexity often hinder model adoption. The research concludes that for models like UrbanSim to be effective, they must be: 1)Transparent to decision-makers and the public. 2)Behaviorally valid, incorporating real-world economic and social factors.3)Empirically validated, ensuring predictions align with observed data. 4) Computationally efficient, allowing real-time scenario evaluation.The paper also highlights the growing role of open-source platforms like OPUS (Open Platform for Urban Simulation) in making these models more accessible to urban planners. | implications for regional transportation plans (RTPs), metropolitan planning organizations (MPOs), and environmental impact assessments. UrbanSim has been used for long-term forecasting, transit-oriented development (TOD) evaluation, and scenario planning. The study suggests that data integration, user-friendly interfaces, and visualization tools are crucial for making complex models more usable in real-world planning contexts. Additionally, it advocates for greater collaboration between researchers, policymakers, and community stakeholders to improve the credibility and adoption of integrated modeling approaches. |

# Appendix E - Urban Sustainability

| Article summary and primary question | Unit of analysis, level of aggregation, and empirical grounding | Primary phenomenon modeled and conclusion | Practical connections |
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| **Alberti and Waddell (2000)** propose an integrated urban development and ecological simulation model that links urban growth, land use change, and environmental impacts. Their primary question is how socioeconomic and ecological processes interact dynamically in metropolitan regions, and how an integrated simulation approach can provide better insights for urban sustainability and growth management policies. This research is part of the Puget Sound Regional Integrated Synthesis Model (PRISM), an initiative to develop interdisciplinary urban and environmental models. The authors build on UrbanSim, a well-established urban simulation model, and extend it to incorporate land conversion, resource use, and emissions as environmental stressors in an evolving urban system. | The model operates at multiple levels of aggregation, using households, businesses, developers, and governments as primary decision-making units, while spatially representing land at the parcel and grid-cell levels. UrbanSim is revised to move from a zonal to a high-resolution grid-based approach, enabling finer spatial interactions between human activities and environmental processes. The empirical grounding includes land use and demographic data, economic activity records, and spatially explicit environmental datasets. The biophysical component integrates models for hydrology, water quality, air pollution, and ecosystem stability, creating a two-way feedback system between urban development and ecological change. | The study models urban land-use change, economic activity, and environmental impacts, emphasizing feedback loops between urban expansion, land consumption, emissions, and ecological degradation. The integrated approach highlights how land development decisions affect and are affected by environmental factors, such as resource availability, ecosystem resilience, and pollution. The authors conclude that traditional urban models, which often assume static equilibrium conditions, fail to capture the complexity of real-world urban dynamics. By incorporating microsimulation, process-based ecological modeling, and spatially explicit feedback mechanisms, the model provides a more realistic and policy-relevant tool for guiding sustainable urban development. | Policymakers can test land-use regulations, infrastructure investments, and environmental policies under different scenarios using this model, helping to minimize negative externalities such as sprawl, pollution, and resource depletion. The authors emphasize that integrating urban and ecological models is essential for improving decision-making and recommend further enhancements in dynamic feedback representation, land-use transition modeling, and agent-based urban simulations. By bridging urban economics, ecology, and complexity science, the study provides a foundation for more holistic and adaptive urban planning frameworks. |
| **Al-Darwish et al. (2018)** develop a hybrid urban growth simulation model combining Cellular | The study operates at a spatial scale of 10m × 10m grid cells, covering urban, agricultural, and | The study models urban expansion patterns, land-use transitions, and their | This work underscores that urban growth management should prioritize vertical expansion |

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| Automata (CA) and Fuzzy Logic, integrated within a Geographic Information System (GIS) framework, to predict future urban expansion in Ibb City, Yemen, and assess its environmental impact. Their primary question is how urban growth trends in Ibb can be simulated and analyzed to inform sustainable planning policies. The study uses historical land-use data (2003 and 2013) to calibrate the model and predict urban growth patterns up to 2033, highlighting the environmental risks associated with uncontrolled urban expansion. | reserved areas in Ibb City. The Cellular Automata-Fuzzy Urban Growth Model (CAFUGM) is employed within the LanduseSim software, incorporating driving factors such as road networks, population density, commercial centers, and urban settlements. Empirical grounding comes from satellite imagery (2003 and 2013), GIS-based land-use data, and urban planning records. The model is validated using a pixel-matching technique, achieving 93.76% accuracy for all land-use layers and 89.40% accuracy for the urban layer. | environmental consequences, particularly the loss of agricultural land and green spaces. Findings indicate that urban areas will expand from 28.41% in 2013 to 43.11% by 2033, primarily at the expense of agricultural and natural landscapes. The results suggest a horizontal expansion trend driven by road infrastructure and dispersed settlements, leading to increased land degradation and reduced ecological balance. The authors conclude that without strategic interventions, uncontrolled urbanization will accelerate environmental deterioration, calling for revised urban planning policies to promote sustainable growth. | strategies rather than uncontrolled horizontal sprawl, particularly in cities with limited land resources. The study recommends that decision-makers regulate sub-road planning, promote high-density development, and establish protected zones for agricultural and ecological preservation to balance urban growth with environmental sustainability. |
| **Leao, Bishop, and Evans (2001)** develop a dynamic urban growth model that integrates geographic information systems (GIS) with system dynamics modeling to assess the long-term demand for landfill sites in urban regions. Their primary question is how urban expansion, population growth, and waste generation dynamics impact the availability of land for waste disposal over time. Using Porto Alegre, Brazil, as a case study, the study quantifies the relationship between land supply and landfill demand, testing different waste management scenarios to evaluate when and | The study operates at two spatial scales: (1) macro-scale urban dynamics, simulating urban growth and waste generation, and (2) micro-scale land suitability analysis, identifying potential landfill locations. The unit of analysis consists of land parcels (30m x 30m grid cells) evaluated for their physical, economic, and environmental suitability for landfill use. Empirical grounding is provided through historical land-use data, demographic trends, and waste production statistics from Porto Alegre's municipal records. The study applies cellular automata (CA) | The study models the spatial and temporal relationship between urban expansion, waste production, and landfill land availability. Findings indicate that landfill demand will outpace available suitable land before 2050, even under moderate waste reduction and recycling scenarios. In the worst-case scenario (no waste reduction measures), Porto Alegre's landfill land supply will be exhausted by 2044, leading to land scarcity for waste disposal. The study concludes that current waste management policies are insufficient to sustain long-term waste disposal needs, and that a | The study emphasizes the need for integrated land-use and waste planning, suggesting that cities should incorporate landfill capacity planning into urban expansion strategies. The findings also highlight that increasing waste recovery through recycling and composting can significantly delay land exhaustion for waste disposal, reinforcing the importance of sustainable waste policies in growing urban areas. |

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| how land shortages for waste disposal will occur. | modeling for urban growth forecasting and multi-criteria decision analysis (MCDA) for landfill site selection. | combination of urban planning policies, landfill site diversification, and increased recycling efforts is necessary to prevent land shortages. | |
| **Liu et al. (2021)** propose a dynamic urban expansion simulation model that integrates Long Short-Term Memory (LSTM) neural networks with Cellular Automata (CA) to predict urban growth while incorporating ecological constraints. Their primary question is how deep learning models can improve the accuracy of urban expansion predictions by addressing time-series dependencies in land-use change data. The study applies the LSTM-CA model to Lanzhou, China, using data from 2000 to 2020 to simulate urban expansion trends and project future growth under two scenarios: natural expansion (NE) and ecological constraint (EC). The results demonstrate that LSTM-CA outperforms traditional ANN-CA and RNN-CA models in simulation accuracy, providing a more reliable tool for sustainable urban planning. | The unit of analysis consists of 30m x 30m grid cells, representing individual land parcels in the Lanzhou metropolitan region. The spatial scale of the model covers five urban districts and three counties, while the temporal scale spans 2000–2030. Empirical grounding is based on multi-source remote sensing data, land-use records, socio-economic indicators, and ecological constraints. The study integrates 14 driving factors (e.g., distance to roads, GDP, population density, and natural land suitability) and employs a Minimum Cumulative Resistance (MCR) model to delineate ecologically protected areas. | The study models spatiotemporal urban expansion while analyzing the impact of ecological constraints on growth patterns. Findings indicate that built-up land in Lanzhou expanded 3.31 times from 2000 to 2020, with urbanization accelerating after 2010. The LSTM-CA model achieved 91.01% accuracy, outperforming ANN-CA and RNN-CA by effectively capturing long-term dependencies in urban growth trends. Simulations for 2030 show that under the NE scenario, urban sprawl continues unchecked, while the EC scenario significantly limits expansion into ecologically sensitive areas. The study concludes that deep learning-enhanced CA models offer a promising solution for urban growth prediction, and that ecological constraints must be integrated into planning strategies to prevent environmental degradation. | The study highlights that proactive zoning regulations and ecological protection policies can mitigate urban sprawl and preserve ecosystem services. The authors recommend expanding the model to incorporate climate change impacts and multi-city comparative analyses, emphasizing the need for adaptive land-use planning frameworks in rapidly urbanizing regions. |
| **Lu et al. (2018)** develop an agent-based model (ABM) to simulate the use of autonomous taxis (aTaxis) for urban | The study operates at the individual commuter and vehicle levels, modeling 20,000 commuters using a GIS-integrated | The study models the impact of replacing personal car commuting with an autonomous taxi fleet, focusing on system efficiency, cost | Authors emphasize that while autonomous taxi fleets can reduce car dependency and improve accessibility, they may also |

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| commuting, evaluating their economic and environmental impacts. Their primary question is how shared autonomous vehicle (SAV) systems compare to personal car commuting in terms of efficiency, cost, and emissions. The study applies the model to Ann Arbor, Michigan, simulating how a fleet of aTaxis could replace conventional private car travel while optimizing fleet size and minimizing wait times. The research assesses travel costs, vehicle utilization, and greenhouse gas (GHG) emissions under different operational scenarios, highlighting the trade-offs between ride-sharing efficiency and increased vehicle miles traveled (VMT) due to empty repositioning trips. | agent-based framework. The agents represent commuters and autonomous taxis, with behavior dictated by travel demand, wait-time tolerance, and ride-sharing preferences. Empirical grounding is based on Ann Arbor's real-world road network, commuting survey data, and traffic statistics, ensuring that simulated trips reflect actual urban conditions. The model is validated using Monte Carlo simulations, testing different fleet sizes, vehicle types (internal combustion vs. electric), and spatial distribution strategies to optimize aTaxis' performance. | savings, and environmental consequences. The findings indicate that a fleet of 4,000 aTaxis (20% of the personal car fleet) can meet commuting demand while keeping wait times under 3 minutes. Compared to private cars, aTaxis reduce total commuting costs by 38% and increase vehicle utilization from 14 to 92 minutes per day. However, VMT increases by 33.6% due to empty repositioning, leading to 16% higher energy consumption, 25% higher GHG emissions, and 10% more SO2 emissions than the baseline scenario. Even with electric aTaxis, environmental performance does not improve significantly due to the high carbon intensity of Michigan's electricity grid. The study concludes that autonomous taxis can reduce commuting costs but may worsen emissions unless policies promote high ride-sharing rates and cleaner energy sources. | increase congestion and emissions if ride-sharing adoption is low. Researchers suggest that regulations promoting shared rides, strategic fleet distribution, and integration with public transit can enhance aTaxis' sustainability benefits. Additionally, energy policies encouraging cleaner electricity grids are crucial to realizing the full environmental benefits of electric autonomous taxis. The study highlights the need for proactive policy interventions to manage the transition to shared autonomous transport systems effectively. |
| **Ma et al. (2018)** develop a dynamic optimization model to analyze the trade-offs between economic growth, energy use, and atmospheric pollution control in resource-based cities in China. Their primary question is how clean energy policies and industrial restructuring can optimize economic development while mitigating air pollution. The | The model operates at the city level, using sectoral economic data, energy consumption statistics, and pollution emissions records to create a multi-sectoral input-output model. The unit of analysis includes economic sectors, residential energy consumption, and transportation systems, with spatial considerations for urban and rural | The study models the dynamic interactions between economic activity, energy consumption, and air pollution emissions, particularly focusing on policy-driven transitions to clean energy. Findings indicate that industrial restructuring and clean energy adoption can significantly reduce SO2 and NOx emissions, with projected declines of 53% and | Authors highlight that clean energy promotion and industrial restructuring are the most effective strategies for pollution reduction, but subsidies and regulatory incentives are necessary to accelerate adoption. Additionally, the study underscores the importance of coordinated regional policies, as pollution reduction in one city may shift emissions to |

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| study applies a linear programming approach based on input-output analysis, integrating three submodels: a socioeconomic submodel, an atmospheric environmental control submodel, and an energy submodel. Using Tangshan City as a case study, the model simulates economic and environmental trends from 2013 to 2025, evaluating the effectiveness of clean energy promotion and industrial restructuring policies in reducing emissions of SO2 and NOx. | areas. Empirical grounding comes from government statistical yearbooks, environmental reports, and regional planning documents, ensuring realistic assumptions about economic structure, pollution control policies, and energy transitions. The model is calibrated using historical data from 2012 and validated against actual economic and pollution trends in Tangshan. | 45%, respectively, by 2025. However, economic growth remains robust, with Tangshan's Gross Regional Product (GRP) increasing by 6.2% annually. The study concludes that integrated policy interventions—including clean energy incentives, industrial subsidies, and transportation reforms—are essential to balancing economic expansion with environmental sustainability. The authors emphasize that resource-based cities must adopt a multi-pronged strategy to achieve long-term atmospheric improvements. | other locations. Future work should incorporate climate change projections and renewable energy scaling to refine long-term sustainability strategies. |
| **Mercure et al. (2016)** critique the reliance on equilibrium-based economic models for sustainability transition policies and propose an alternative complex systems approach that incorporates heterogeneous agents and dynamic feedbacks. Their primary question is how a complexity-based, agent-driven modeling framework can more effectively inform sustainability policy, particularly in areas like technology adoption, macroeconomic impacts, socio-environmental interactions, and policy anticipation. The paper identifies five key shortcomings of traditional optimization-based models: their normative assumptions, overreliance on fully | The study's unit of analysis varies based on the modeled system but centers on heterogeneous economic agents, including consumers, firms, and policymakers. Unlike equilibrium models that assume representative agents, this approach emphasizes individual decision-making diversity and interactive behavior at multiple levels of aggregation. The empirical grounding comes from historical technology adoption patterns, macroeconomic data, and environmental system models, integrated through statistical modeling and scenario-based simulations. The framework builds on behavioral economics, evolutionary | The paper models policy-driven sustainability transitions by examining technology diffusion, macroeconomic dynamics, environmental feedbacks, and policy effectiveness. The authors demonstrate that traditional equilibrium models systematically underestimate the complexity of sustainability transitions, leading to misguided policy recommendations such as an overreliance on carbon pricing as a singular solution. The complexity-based approach reveals path dependencies and tipping points in technological change, emphasizing the need for multi-pronged policy interventions rather than single-policy optimizations. The study | The proposed modeling approach allows policymakers to assess policy interactions, market feedback loops, and uncertainty propagation across economic sectors. By moving beyond equilibrium-based assumptions, this framework enables more accurate evaluations of green technology subsidies, employment shifts from low-carbon investments, and the cascading effects of policy decisions across industries. The authors argue that integrating complexity science into policy modeling can bridge the gap between theoretical economic predictions and real-world policy outcomes, offering a more adaptive and responsive approach to sustainability planning. |

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| rational agents, exclusion of multi-agent interactions, neglect of path dependency, and failure to incorporate agent heterogeneity. The authors advocate for a non-equilibrium, simulation-based methodology that better captures real-world decision-making and system feedbacks. | economics, and complexity science, incorporating insights from finance, climate science, and industrial organization. | concludes that integrating non-equilibrium models into climate and energy policy design leads to more robust and realistic forecasts, ultimately improving decision-making under uncertainty. | |
| **Reinhart et al. (2013)** introduce UMI (Urban Modeling Interface), an urban simulation tool designed to evaluate building energy use, daylighting, and walkability at the neighborhood scale. The primary question the paper addresses is how an integrated urban modeling platform can support sustainable neighborhood design by combining multiple performance metrics. Unlike traditional simulation tools that focus on individual buildings, UMI enables planners and architects to assess energy performance, daylight access, and mobility patterns across entire districts. The tool is built on Rhinoceros 3D, using EnergyPlus for energy modeling, Radiance/Daysim for daylighting, and custom scripts for walkability analysis. The study presents UMI's capabilities through a case study of a mixed-use development in Boston, USA. | The unit of analysis in UMI is the neighborhood, with buildings represented as individual 3D massing models. The tool operates at both the building and street scales, allowing for aggregated energy, daylighting, and transportation assessments. Empirical grounding comes from real-world urban design scenarios, using building energy benchmarks (DOE Commercial Building Benchmark Models), climate-adjusted urban weather data, and GIS-based walkability metrics. The case study in Boston demonstrates how UMI's simulations align with urban planning principles by evaluating different zoning, land-use, and massing configurations. | UMI models the interconnections between building energy consumption, daylighting, and walkability to assess urban sustainability. The energy simulation component, powered by EnergyPlus, evaluates heating, cooling, and lighting demands while accounting for factors such as urban heat island effects, shading, and building massing. The daylighting analysis, using Radiance/Daysim, estimates daylight autonomy and solar exposure to assess both visual comfort and potential energy savings from reduced artificial lighting. Additionally, UMI integrates a walkability analysis that considers street connectivity, proximity to amenities, and land-use mix to measure how pedestrian-friendly a neighborhood is. The study finds that UMI successfully bridges architectural-scale modeling with broader urban planning concerns, providing a comprehensive simulation framework for | UMI's applications seem to be relevant for urban planners, architects, and policymakers seeking data-driven approaches to sustainable city design. The tool helps optimize street layouts, building configurations, and zoning regulations by providing actionable insights into energy efficiency, daylighting, and pedestrian-friendly environments. Compared to static GIS-based tools, UMI's dynamic simulation approach allows designers to test alternative urban growth scenarios and evaluate their long-term environmental impacts. The study suggests that further development could integrate transportation emissions, microclimate effects, and more detailed human behavior modeling to enhance urban sustainability assessments. |

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| | | evaluating design trade-offs. The tool allows for iterative testing of urban configurations, helping designers optimize building orientation, zoning, and massing to balance energy efficiency, daylight access, and sustainable mobility. The results suggest that incorporating multiple performance metrics within a single modeling environment can significantly enhance decision-making in early-stage urban design. | |
| **Xu and Coors (2012)** present an integrated GIS-system dynamics (GISSD) approach for evaluating the sustainability of urban residential development by combining system dynamics (SD), geographic information systems (GIS), and 3D visualization techniques. Their primary question is how integrating SD modeling with spatial analysis can improve sustainability assessment and decision-making in urban development. The study applies the DPSIR (Driving Forces, Pressure, State, Impact, and Response) framework to define sustainability indicators and uses multi-criteria analysis (MCA) and analytic hierarchy process (AHP) to weigh different indicators. The approach is tested through a case study of Stuttgart, Germany, modeling housing demand, economic factors, environmental | The study operates at two levels of analysis: (1) a temporal system dynamics model (SD) simulating interactions between economic, social, environmental, and housing subsystems, and (2) a spatial GIS-based analysis, visualizing urban development trends through 2D density maps and 3D city models. The model integrates 24 sustainability indicators, categorized into five DPSIR components, and is validated using historical data from the State Statistical Bureau of Baden-Württemberg (Germany). The study applies multi-scale spatial resolution, from regional sustainability trends to neighborhood-level building distributions, demonstrating the feasibility of integrating GIS with dynamic simulation methods. | Results indicate that housing supply in Stuttgart will continue to grow until 2020, with per capita living space expanding and the housing supply-demand ratio remaining stable. However, economic growth and population shifts exert pressures on environmental resources, including increased $CO_2$ emissions, air pollution, and domestic water consumption. The model successfully forecasts sustainability trends and visualizes spatial variations in urban development, supporting long-term planning. The authors conclude that integrating SD, GIS, and 3D visualization enhances sustainability assessment by linking spatial patterns with temporal dynamics, making it a valuable tool for policymakers. | The GISSD framework allows planners to simulate housing demand, predict environmental impacts, and visualize different growth strategies, making it particularly useful for urban expansion management, zoning decisions, and infrastructure planning. The 3D visualization component improves communication with stakeholders by depicting urban growth scenarios in an intuitive, interactive format. The study suggests that future research could incorporate real-time data, climate change projections, and participatory planning tools to further enhance the model's applicability in sustainability governance. |

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| pressures, and social dynamics over a 30-year period (1991–2020). | | | |
| **Xu and Coors (2012)** present an integrated GIS-system dynamics (GISSD) approach for evaluating the sustainability of urban residential development by combining system dynamics (SD), geographic information systems (GIS), and 3D visualization techniques. Their primary question is how integrating SD modeling with spatial analysis can improve sustainability assessment and decision-making in urban development. The study applies the DPSIR (Driving Forces, Pressure, State, Impact, and Response) framework to define sustainability indicators and uses multi-criteria analysis (MCA) and analytic hierarchy process (AHP) to weigh different indicators. The approach is tested through a case study of Stuttgart, Germany, modeling housing demand, economic factors, environmental pressures, and social dynamics over a 30-year period (1991–2020). | The study operates at two levels of analysis: (1) a temporal system dynamics model (SD) simulating interactions between economic, social, environmental, and housing subsystems, and (2) a spatial GIS-based analysis, visualizing urban development trends through 2D density maps and 3D city models. The model integrates 24 sustainability indicators, categorized into five DPSIR components, and is validated using historical data from the State Statistical Bureau of Baden-Württemberg (Germany). The study applies multi-scale spatial resolution, from regional sustainability trends to neighborhood-level building distributions, demonstrating the feasibility of integrating GIS with dynamic simulation methods. | Results indicate that housing supply in Stuttgart will continue to grow until 2020, with per capita living space expanding and the housing supply-demand ratio remaining stable. However, economic growth and population shifts exert pressures on environmental resources, including increased $CO_2$ emissions, air pollution, and domestic water consumption. The model successfully forecasts sustainability trends and visualizes spatial variations in urban development, supporting long-term planning. The authors conclude that integrating SD, GIS, and 3D visualization enhances sustainability assessment by linking spatial patterns with temporal dynamics, making it a valuable tool for policymakers. | The GISSD framework allows planners to simulate housing demand, predict environmental impacts, and visualize different growth strategies, making it particularly useful for urban expansion management, zoning decisions, and infrastructure planning. The 3D visualization component improves communication with stakeholders by depicting urban growth scenarios in an intuitive, interactive format. The study suggests that future research could incorporate real-time data, climate change projections, and participatory planning tools to further enhance the model's applicability in sustainability governance. |