

Agent-Based Modeling and Simulation for Resilient and Sustainable Smart City Planning in Saudi Arabia

Abstract

Saudi Arabia is at the same time working towards rapid urban transformation, digitalization, climate adaptation, the modernization of its infrastructure, and an improvement in the quality of life. The fact that it has set these aims leads to a planning problem which cannot easily be solved by using general forecasting methods since the results of urban development result from the interactions between households, travelers, firms, utilities, public agencies, infrastructure, and environmental conditions. This review looks at the role of agent-based modelling and simulation in helping to achieve resilient and sustainable smart city planning in Saudi Arabia. It draws together peer-reviewed literature published between 2020 and 2025 on agent-based modelling, urban digital twins, transport, energy, infrastructure resilience, and the development of smart cities in Saudi Arabia. The review makes use of a structured integrative approach which involves transparent database searching, thematic coding, methodological appraisal, and cross-domain synthesis, without stating any unverified figures for the number of studies screened. The findings indicate that agent-based methods are especially useful for depicting heterogeneous behaviour, testing disruptive scenarios, examining policy feedbacks, and connecting individual-level decisions to overall system outcomes. Yet the usefulness of such models depends on behavioural validity, calibration, uncertainty analysis, data governance, interoperability, and clear documentation. For Saudi cities, the greatest opportunity is to combine agent-based simulation with geographic information systems, urban digital twins, data from the Internet of Things, and participatory planning. A six-layer planning framework is suggested, linking urban agents, spatial infrastructure, behavioural rules, disruption scenarios, resilience and sustainability indicators, and adaptive policy feedback. The review ends by saying that agent-based modelling should not be seen as a predictive oracle but rather as a policy laboratory in which plausible futures can be compared, vulnerabilities identified, and robust interventions designed in the face of uncertainty.

1. Introduction

The urban development programme in Saudi Arabia is now at a stage where traditional master-planning tools have to be used in conjunction with digital platforms, real-time sensing, large-scale infrastructure projects, and the country's ambitious sustainability goals. The cities of Riyadh, Jeddah, Dammam, Makkah, Madinah, and the other newly planned areas each have their own combination of mobility requirements, extreme heat, limitations regarding water supply, high energy intensity, changes in land use, expectations concerning public services, and vulnerability to disruptions. As a result, the nation's smart city initiatives need approaches that can account for both the physical systems and the behaviour of people and institutions. Recent research carried out in Saudi Arabia has stressed the importance of strategic smart city frameworks, citizen participation, urban resilience, transit-oriented development, and the environmental aspects of Vision 2030 (Alshuwaikhat et al., 2022; Almatar, 2022; Alamoudi et al., 2023; Aldegheishem, 2023; Almulhim and Cobbinah, 2024). It has become evident from these studies that technology by itself is not enough to ensure sustainable or resilient urban performance; governance, behaviour, inclusion, and adaptive capacity are still at the heart of the matter.

Agent-based modelling (ABM) offers a complementary approach since it depicts a system using autonomous and diverse agents which perceive the circumstances, adhere to rules or decision models, interact with one another, and alter their behaviour over time. The resulting system outcomes are derived from these local interactions rather than being the result of aggregate equations alone. This aspect is particularly important in the case of cities, as problems such as congestion, energy demand, evacuation, the adoption of technology, choices regarding housing, access to services, and social responses usually result from decentralized decisions. Current reviews indicate that ABM has progressed from being limited to standalone conceptual experiments to being used in fields such as construction, architecture, transport, climate policy, social-ecological systems, and digital twins (Khodabandelu and Park, 2021; An et al., 2021; Stieler et al., 2022; Secchi et al., 2024; Mazzetto, 2024). ABM is therefore well placed to assist

with integrated smart city planning, on the condition that its assumptions are made clear and that the models are appropriately calibrated and validated.

The argument in favour of using ABM in Saudi Arabia is made stronger by the extent of the Kingdom's transformation. As part of its smart city initiatives, more and more attention is being paid to combining physical infrastructure with digital services, and urban resilience requires preparation for the effects of climate stress, network failures, emergency situations, and unexpected changes in human behaviour. Although urban digital twins provide a rich source of data about city assets and the processes that take place within them, they become more valuable from an analytical point of view when they also include representations of human and organisational decision-making. Research into smart cities that make use of digital twins has identified data integration, real-time updating, scenario analysis, and decision support as key capabilities (Wang et al., 2023). Similarly, research into human-centred urban digital twins calls for the inclusion of multi-agent interactions and coupled social, physical and natural systems when the aim is to achieve resilience (Ye et al., 2023). ABM can provide this behavioural element, allowing planners to ask not only what infrastructure is in place but also how different actors might respond when conditions, prices, policies, risks or information change.

Yet agent-based simulation is by no means automatically credible. Although the flexibility which gives it power may lead to rules that are only weakly justified, excessive parameterization, limited reproducibility, and overconfident claims about scenarios. Reviews of agent decision-making stress the importance of justifying behavioural formulations in light of the specific context rather than viewing the agents as generic rational optimizers (Wijermans et al., 2023). Other methodological studies point out difficulties concerning the use of theory, model transparency, calibration, the computational burden, and transferability (Antosz et al., 2023; Agriesti et al., 2023). These issues are very relevant in the Saudi context since rapid urban change means that historical data might not adequately reflect future behaviour and since behavioural assumptions imported from elsewhere may not be suitable for the local social, climatic, and institutional conditions.

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89 The review thus regards ABM as a decision-support method for examining possible urban
90 futures rather than as a tool for generating single-point forecasts. It makes three contributions.
91 The first is to bring together the latest evidence in relation to the planning areas most pertinent to
92 Saudi smart cities: mobility and accessibility, energy and buildings, infrastructure and emergency
93 resilience, citizen and institutional behaviour, and digital twin integration. The second is to
94 establish the methodological conditions under which ABM results are robust enough to assist in
95 planning. The third is to suggest an integrated framework adapted to Saudi Arabia which
96 connects heterogeneous agents and spatial systems to resilience, sustainability, and governance
97 indicators. The main point is that the greatest benefit of ABM is in showing interaction effects,
98 thresholds, inequalities, and unintended consequences which cannot easily be observed using
99 static or aggregate methods alone.

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101 **2. Aim, Objectives and Research Questions**

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103 This review aims to assess the way in which agent-based modelling and simulation can
104 contribute to enhancing resilient and sustainable smart city planning in Saudi Arabia and to
105 develop a practical integrative framework for use in future urban decision support.

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107 The study is guided by four objectives. The first of these is to bring together the most recent
108 methodological developments in ABM that are pertinent to complex urban systems. The second
109 objective is to look at the way ABM has been used in the areas of mobility, energy, buildings,
110 infrastructure resilience, and crisis behaviour. The third involves linking these applications to the
111 specific planning priorities and constraints mentioned in recent Saudi smart city literature. The
112 fourth objective is to spot the existing research gaps and to establish a framework for combining
113 ABM with spatial data, digital twins, sensing systems, and participatory governance.

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The review looks at four questions: How is it possible for ABM to represent the interacting behavioural and infrastructural processes which shape Saudi smart cities? In which application areas is there the strongest evidence for resilience and sustainability planning? What methodological limitations need to be overcome before the results of the simulation can be used in policy? And how can agent-based simulation be combined with urban digital twins and Saudi planning institutions in order to support adaptive, evidence-informed decisions?

3. Review Methodology

A structured integrative review approach was chosen since the subject area involves a number of different disciplines and includes diverse types of evidence such as methodological reviews, simulation studies, research into urban planning, transport modelling, energy systems, infrastructure resilience, and work on smart cities in Saudi Arabia. This method was guided by recent reviews of agent-based models which combine systematic retrieval with conceptual classification and thematic synthesis (Khodabandelu and Park, 2021; Mazzetto, 2024). Because the variety of the evidence meant that pooled effect estimates could not be calculated, the synthesis instead concentrated on mechanisms, model design decisions, application patterns, and planning implications.

The search was based on four main conceptual categories: agent-based modelling or simulation; smart cities, urban systems, digital twins, or urban planning; resilience, sustainability, mobility, energy, infrastructure, or crisis management; and Saudi Arabia, Riyadh, Vision 2030, or similar hot-arid urban environments. The literature was found using Scopus, Web of Science, IEEE Xplore, ScienceDirect, and the databases of the publishers, and direct relevant peer-reviewed papers were located by means of citation tracing. Only English-language journal articles published between 2020 and 2025 were included. Preference was given to papers that had methodological relevance, applied urban planning techniques, achieved resilience or sustainability outcomes, or were relevant to Saudi planning. Papers that were solely from conferences, preprints, contained only technical algorithms without a connection to urban

144 planning, and those that did not provide adequate methodological details were not used as
145 primary evidence.

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147 The set of references employed in this manuscript consists of thirty studies that have been peer-
148 reviewed. Since the search was carried out in an iterative manner and refined as it progressed
149 through various databases, there is no assertion regarding the number of records initially
150 obtained. Each study that was kept was assigned a code according to six dimensions: the problem
151 domain, the type of agent, the environment and its spatial representation, the behavioural or
152 decision logic, the calibration and validation approach, and the policy-relevant outcomes. A
153 second coding category was used to indicate whether the study dealt with resilience,
154 sustainability, equity, digital twin integration, or governance. This two-stage coding system
155 enabled comparisons to be made between applications that would otherwise be very different.

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157 The methodological quality was assessed by means of a fit-for-purpose evaluation rather than by
158 assigning a numerical score. Evidence was regarded as stronger when there were explicit
159 definitions of the agents, documented rules regarding behaviour, empirical or data-based
160 calibration, sensitivity or uncertainty analysis, a transparent scenario design, and some form of
161 validation based on observed patterns or independent evidence. This method takes into account
162 the concern regarding the difference between simulations that look realistic and those that can
163 justify the decisions they support (An et al., 2021; Wijermans et al., 2023). In the case of high-
164 dimensional calibration it may be necessary to use advanced optimization techniques since many
165 parameters interact (Agriesti et al., 2023). Therefore, a model that is visually detailed was not
166 considered to be more valid than a simpler one that is well documented.

172 Table 1. Minimum methodological requirements for policy-grade agent-based modeling.

Stage	Required practice	Evidence / validation	Main failure if omitted
Problem framing	Define the decision question, system boundary, time horizon and policy levers.	Planning mandate, stakeholder review and explicit scope.	Model complexity without decision relevance.
Agent design	Specify agent types, attributes, constraints and decision logic.	Surveys, observations, theory and documented institutional rules.	Plausible-looking but unsupported behavior.
Spatial/data integration	Align GIS, networks, assets, climate and service data with model states.	Data provenance, temporal resolution and missing-data checks.	Misaligned or stale representation of urban conditions.
Calibration	Estimate or tune influential parameters against observed patterns.	Travel, demand, choice, service or operational observations.	Arbitrary tuning or overfitting.
Validation	Test structural, behavioral and emergent patterns.	Held-out observations, independent evidence and stakeholder checks.	False confidence in scenario outputs.
Uncertainty & sensitivity	Vary parameters, behaviors and scenarios systematically.	Sensitivity analysis, ensembles and alternative assumptions.	Brittle policy conclusions.
Documentation & governance	Version assumptions, code, data access and privacy	Reproducibility log, ownership and independent	Weak accountability and poor

Stage	Required practice	Evidence / validation	Main failure if omitted
	controls.	review trail.	transferability.

The process took place in three stages. In the first stage, the studies were divided into different thematic planning areas. In the second stage, the enabling mechanisms and limitations that occurred repeatedly within the various domains were recognised. In the third stage, the findings were compared with the Saudi smart city priorities as stated in recent literature, specifically mentioning strategic implementation, participation, mobility transformation, resilience, and environmental performance. Since the framework produced is an analytical synthesis and not an empirically calibrated model of Saudi cities, it is meant to help direct future modelling initiatives, data gathering, and policy experiments while clearly distinguishing between what has already been shown in the literature and what still needs to be tested locally.

4. Thematic Literature Review and Critical Analysis

Agent-based modelling as a method in the field of urban planning. It is useful in cases where the behaviour of the entire system is influenced by heterogeneous choices, local interactions, path dependence, or feedback. In the context of urban development, agents can stand for households, developers, businesses, travellers, utilities, public agencies, emergency services, or even parts of the infrastructure. González-Méndez et al. (2021) show how urban development planning can be based on human needs rather than merely on market aggregates, thus demonstrating the ability of agent-based modelling to link individual preferences with spatial results. Secchi et al. (2024) also claim that agent-based approaches can formalise sustainability theories by making the assumptions explicit and testable. This is especially significant for smart city planning in Saudi Arabia since the sustainability objectives involve interconnected social, economic, environmental and technological processes rather than separate engineering variables.

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198 The reason why ABM has a methodological advantage is not that it achieves perfect realism, but
199 rather that it offers a controlled setting in which heterogeneous assumptions can be examined. An
200 et al. (2021) point out both the opportunities and the unresolved challenges involved in
201 modelling agent-based complex systems, such as data integration, behaviour, scale, and
202 validation. Antosz et al. (2023) go on to say that theory can carry out a number of roles in agent-
203 based research and should not be used in a vague way. In the context of city planning, this
204 implies that each behavioural rule must have a clear justification—commuters might aim to
205 minimise their general travel cost, households might place a value on accessibility and thermal
206 comfort, firms might react to incentives and changes in demand, and public agencies might
207 distribute their resources within budget and service limitations. The rules should be regarded as
208 hypotheses to be tested, not as hidden mechanisms that determine in advance the outcomes that
209 are desired.

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211 Mobility, accessibility, and the transition in transport systems. Transport is one of the most
212 developed areas for the application of agent-based methods. Huang et al. (2022) demonstrate that
213 ABM is able to represent travelers' beliefs, preferences, their ability to adapt, and interactions
214 within networks over a range of time scales. Li et al. (2021) do the same when it comes to
215 applications involving autonomous vehicles and show that agent-level simulation is valuable for
216 the study of future mobility and logistics systems. In the case of Saudi Arabia, these capabilities
217 are applicable to transit-oriented development, first- and last-mile access, the dependence on
218 private vehicles, shared mobility, autonomous transport, and the large investments being made in
219 public transport. Almatar (2022) considers transit-oriented development to be an important route
220 for Riyadh, but the results of such strategies will depend on how households and travelers
221 actually respond to density, access to stations, the quality of service, parking, exposure to heat,
222 and the availability of other means of travel.

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224 An airport-based mobility model for Riyadh could therefore be used to simulate travellers who
225 have a variety of trip purposes, different income levels, various degrees of access to vehicles,

differing tolerances for walking, a range of schedule constraints, and different preferences regarding comfort or reliability. The environment it takes into account could comprise the road network, the metro and bus systems, the pattern of land use, parking facilities, shaded paths for pedestrians, and the frequency of services. Scenarios might examine the effects of increasing density in station areas, introducing parking pricing, improving feeder services, adopting flexible working arrangements, introducing autonomous shuttles, or developing pedestrian infrastructure that adapts to heat. Calibration would need to make use of travel surveys, smart-card records, traffic counts, aggregates from mobile devices, and observations at the station level. Agriesti et al. (2023) demonstrate that advanced calibration methods can aid in managing high-dimensional transport models, but local behavioural evidence is still essential. The policy value would lie in comparing the distributions of travel time, accessibility, emissions, mode share, and exposure rather than simply reporting the average network performance.

Mobility ABM also has a direct effect on resilience. By means of modelling the behaviour of agents and the damaged infrastructure after an earthquake, Feng et al. (2020) show that emergency travel patterns can differ greatly from those under normal circumstances. This kind of approach can be applied to situations such as flash floods, road closures, dust storms, infrastructure failures, or the movement of large crowds. Resilience planning in Saudi cities should therefore take into account behaviour that is specific to each type of disruption rather than assuming that normal travel demand will occur during an emergency. The simulation should be used to check whether emergency routes, hospitals, evacuation zones, and additional transport capacity remain accessible when both the infrastructure and people's decisions change at the same time.

The sustainability of smart cities is greatly based on the way in which buildings, their occupants, energy systems, and policy incentives interact. According to Akhatova et al. (2022), agent-based models are appropriate for achieving decarbonisation in district energy systems since they are able to account for various stakeholders, different technology options, and policy reactions. Su and Wang (2020) show a distributed agent-based control method for the heating, ventilation, and air-conditioning systems of buildings within smart sensor networks. Even though the cooling

demand in Saudi Arabia is different from that seen in many temperate regions, the fundamental principle remains relevant in that decentralised agents can respond to local conditions at the same time as helping to improve overall system efficiency.

When it comes to Saudi Arabia's planning, an urban energy agent-based model (ABM) could include representations of households, building owners, energy service companies, distributed generation assets, electric vehicles, and grid operators. The agents could decide on cooling settings, retrofitting measures, the installation of rooftop solar panels, the use of storage systems, charging times, or participation in demand response according to tariffs, comfort levels, the information available to them, and their capital limitations. The model could link decisions made at the building level with district-wide electricity peaks, emissions, and grid stress. This is particularly important since the environmental assessments of Vision 2030 still highlight the significance of energy-related emissions and the necessity of continuing to implement decarbonisation measures (Altouma et al., 2024). A key area for research is to model rebound effects and behavioural adaptation; technical efficiency improvements may not result in proportional decreases in consumption if at the same time people's comfort expectations, the floor area of buildings, or the use of devices also change.

For a city to be resilient it is necessary to have more than just strong individual components since failures can spread across the areas of transport, electricity, communications, water, logistics and social services. By means of agent-based approaches the interdependencies can be shown by having the various parts of the infrastructure, their operators and the users react to changing conditions. Thus, Fan et al. (2024) apply an agent-based simulation to look at panic buying in the course of urban public crises and demonstrate the way in which the government, the media and social networks affect collective behaviour. The broader implication is that the flow of information can either increase or reduce disruption, which means that resilience models should incorporate communication and trust rather than viewing citizens as passive units of demand.

Digital communication falls within the area of resilience. Alenazi (2024) has suggested a system for enhancing the communication networks of smart cities by means of network design, with a focus on ensuring the continued operation of essential services in the face of disruptions. In an integrated Saudi agent-based model, the availability of communication could affect decisions about routes, compliance with emergency measures, the making of service requests, and coordination between institutions. The model could examine the situation in which digital systems are only partly unavailable, when inaccurate information spreads, or when different groups in the population have unequal access to alerts. This would mean that the evaluation of resilience moves from a focus on the robustness of assets to one on service continuity and adaptive behaviour.

The use of digital twins and their integration with multiple agents. Digital twins are becoming known as the operational core of smart cities since they have the ability to link together physical assets, sensors, data platforms, analytics, and visualisation methods. Wang et al. (2023) point out that real-time data management, interoperability, and decision support are the key issues in smart cities that make use of digital twins. Ye et al. (2023) claim that urban digital twins which are meant to enhance community resilience must be people-oriented and incorporate social, physical, and natural systems. ABM supports this approach by providing explicit representations of people and organisations whose behaviour cannot be reliably inferred from infrastructure data alone.

The most effective kind of architecture is not one that incorporates ABM as an optional, decorative simulation layer on top of a digital twin, but rather a two-way system in which data obtained from observation are used to update the states of the agents and the results of the simulation in turn influence operational or strategic decisions. Qiu et al. (2023) demonstrate how agent-based discrete-event simulation can be combined with an evolutionary digital twin and adaptive learning. Li et al. (2024) present a similar multi-agent digital twin approach for providing sustainable and resilient decision support in a complex supplier system. Even though these studies do not involve city-scale applications in Saudi Arabia, they do show principles that can be transferred: modular agents, state synchronization, scenario experimentation, feedback, and decision validation. Smart city planners can apply the same reasoning to connect traffic

sensors, building energy data, service requests, environmental monitoring, and the condition of the infrastructure to a continuously updated scenario platform.

Machine learning could also contribute to this level of integration, but it ought not to take the place of explicit causal reasoning. Zhang et al. (2023) examine the complementary functions of machine learning and ABM, covering areas such as behavioural inference, emulation, and adaptive decision making. Machine learning is able to identify patterns from data, whereas ABM can investigate how these patterns would interact under counterfactual policies. In the context of use in Saudi Arabia, this approach could be used to work out mobility preferences, energy-use patterns, or service demand from large datasets and then incorporate those estimates into transparent scenario models. The primary concern is that the opaque learned behaviour might make the model more difficult to interpret. Hence, for decisions involving distributional effects, explainability and sensitivity analysis are just as important as the accuracy of the predictions.

The context for Saudi Arabia's strategy and planning concerning smart cities is well defined in the country's own literature. Alshuwaikhat et al. (2022) suggest a framework based on the product life cycle for carrying out smart and sustainable initiatives in Riyadh, stressing the need for strategy, implementation, monitoring, and ongoing improvement. Alamoudi et al. (2023) stress the importance of citizen participation and the involvement of various stakeholders in the implementation of smart and sustainable cities. Aldegheishem (2023) assesses the progress made in Saudi smart cities across a number of dimensions such as the economy, people, the environment, living conditions, mobility, and governance. These views indicate that a Saudi agent-based model (ABM) should not be confined to traffic or energy engineering; it should connect technical performance with participation, governance, service equity, and quality of life.

Urban resilience introduces an additional level of policy. Almulhim and Cobbinah (2024) claim that when considering urban resilience in Saudi Arabia it should be looked at in terms of climate change, land-use planning, disaster management, green infrastructure, digital technology, institutions, and participation. Almulhim (2025) also identifies governance, stakeholder

collaboration, sustainability, public satisfaction, and integrated planning as the main elements of resilient smart cities. Using ABM, these ideas can be put into practice by turning them into scenario variables and into measurable interactions. For instance, planners might compare a centralised approach to emergency management with one based on response networks at the neighbourhood level, or examine the effect of participation on the adoption of water conservation, public transport, or heat adaptation measures.

The introduction of large-scale projects increases complexity as well. Yusuf and Abdulmohsen (2023) use NEOM as an example when considering sustainable planned cities, at the same time pointing out the considerable uncertainties and risks involved in implementation. Instead of viewing planned cities as empty canvases, agent-based simulation can show how the intended designs interact over time with human preferences, labour markets, visitor demand, logistics, affordability and operational constraints. It is particularly useful for detecting path dependence: after residents, firms and infrastructure networks have developed routine patterns, subsequent policy changes might lead to different results than those which would be expected from static design assumptions. In the case of Saudi Arabia, simulation should therefore be applied before, during and after implementation, not just during the master planning stage.

The issue of model credibility, validation, and uncertainty. In all fields, credibility is the main obstacle to the use of such models. Mazzetto (2024) illustrates the wide range of applications of ABM but also stresses the need for greater integration, more methodological transparency, and further research. Stieler et al. (2022) too point out the limitations and problems relating to classification in the case of architectural ABM. The key takeaway for the field of smart cities is that visual complexity should not take the place of validation; a city model might have detailed three-dimensional geometry and yet be based on weak assumptions regarding human behaviour.

Saudi models that are to be regarded as credible should therefore adopt a multi-layered approach to validation. Firstly, structural validation must ensure that the agents, networks, and institutional relationships in the model match those of the actual system. Secondly, behavioural validation

372 should involve comparing the decision patterns with the results of surveys, observed choices, or
 373 experiments. Thirdly, pattern validation should check whether the simulation accurately
 374 reproduces spatial and temporal distributions such as traffic flows, energy peaks, service
 375 demand, or evacuation times. Sensitivity analysis needs to determine which parameters have a
 376 significant effect on the policy conclusions. Scenario uncertainty must be presented in the form
 377 of a range of possible outcomes and alternative behavioural assumptions rather than relying on a
 378 single preferred future. Lastly, stakeholder validation should include planners, operators,
 379 representatives of the community, and experts in the field in the process of reviewing whether the
 380 assumptions made are reasonable. This approach helps to lower the risk that a model which is
 381 technically well-made will become detached from local reality.

382 Table 2. Principal ABM application domains and their relevance to Saudi smart city planning.

Planning domain	Representative agents	Key inputs	Resilience / sustainability outcomes	Saudi planning use
Mobility & accessibility	Travelers, vehicles, operators	GIS networks, traffic, transit, smart-card and survey data	Travel time, accessibility, emissions, redundancy	TOD, feeder services, parking and heat-adaptive access
Energy & buildings	Households, owners, utilities, EVs	Meters, weather, building stock, tariffs	Peak load, cooling demand, emissions, recovery	District cooling, demand response, retrofit and solar adoption
Infrastructure & emergencies	Users, responders, road links, health facilities	Network status, hazard, capacity and emergency demand	Response time, service continuity, cascading failure	Route continuity and disruption stress tests
Water &	Households,	Consumption, supply,	Conservation,	Water-saving

Planning domain	Representative agents	Key inputs	Resilience / sustainability outcomes	Saudi planning use
resources	utilities, facilities	service availability	shortage exposure, service equity	incentives and resource allocation
Communications & data	Network nodes, agencies, citizens	Topology, availability, alerts and service status	Reachability and information continuity	Backup communications and resilient digital services
Citizens & governance	Residents, agencies, firms, communities	Surveys, participation, service requests	Adoption, trust, equity and distributional impact	Participatory scenario design and policy acceptance

5. Discussion

The available evidence indicates that the way smart city simulation is seen in Saudi planning should now change. ABM should not be regarded as a replacement for traditional forecasting, engineering analysis, or strategic planning; its key advantage lies in its ability to show the interaction effects between different actors and systems. Although aggregate models are efficient at estimating travel demand, energy consumption, or population growth, agent-based models are capable of explaining why distributions change, who benefits, how behaviour adjusts, and where nonlinear thresholds occur. Hence, the two methods are complementary.

A Saudi framework which is practical (as shown in Figure 1) can be divided into six interacting layers. The first of these layers sets out the agents, namely residents, visitors, firms, developers, transport users, utilities, agencies, emergency responders, and digital service providers. The

second layer depicts the urban environment by means of land use, buildings, networks, public spaces, environmental conditions, and service capacity. The third includes the decision rules and rules regarding interaction which are based on local evidence. The fourth incorporates various scenarios such as policy interventions, growth, heat, infrastructure outages, economic shocks, or emergency events. The fifth evaluates the outcomes in terms of resilience, sustainability, equity, accessibility, emissions, resource use, and service continuity. The sixth establishes an adaptive feedback loop by having the results examined by institutions and stakeholders, updating the parameters with new data, and then retesting the policies.

Integrated Agent-Based Planning Architecture

A policy laboratory linking observed urban conditions, heterogeneous behavior, scenarios and adaptive decisions

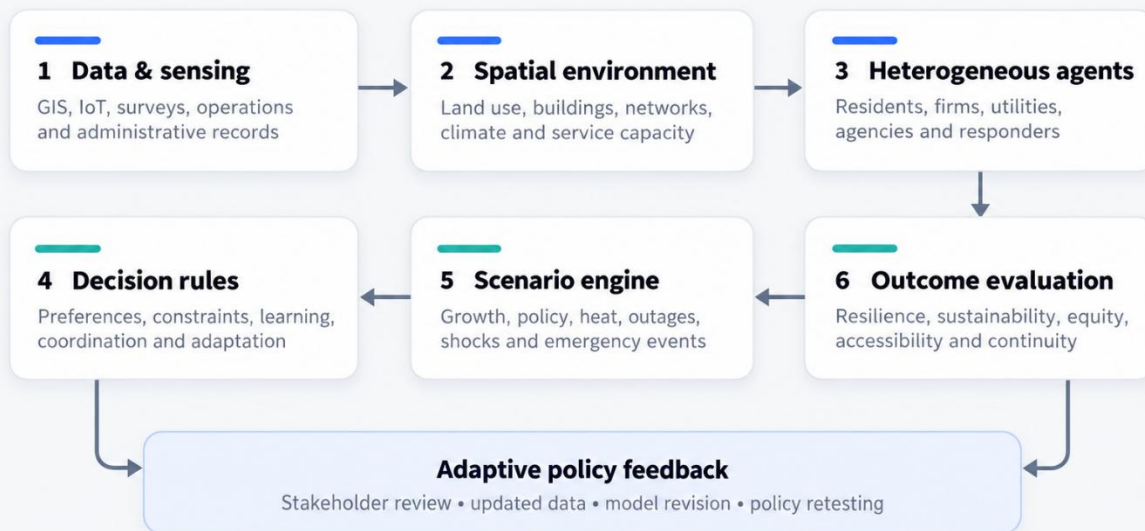


Figure 1. Proposed integrated agent-based planning architecture for resilient and sustainable Saudi smart cities.

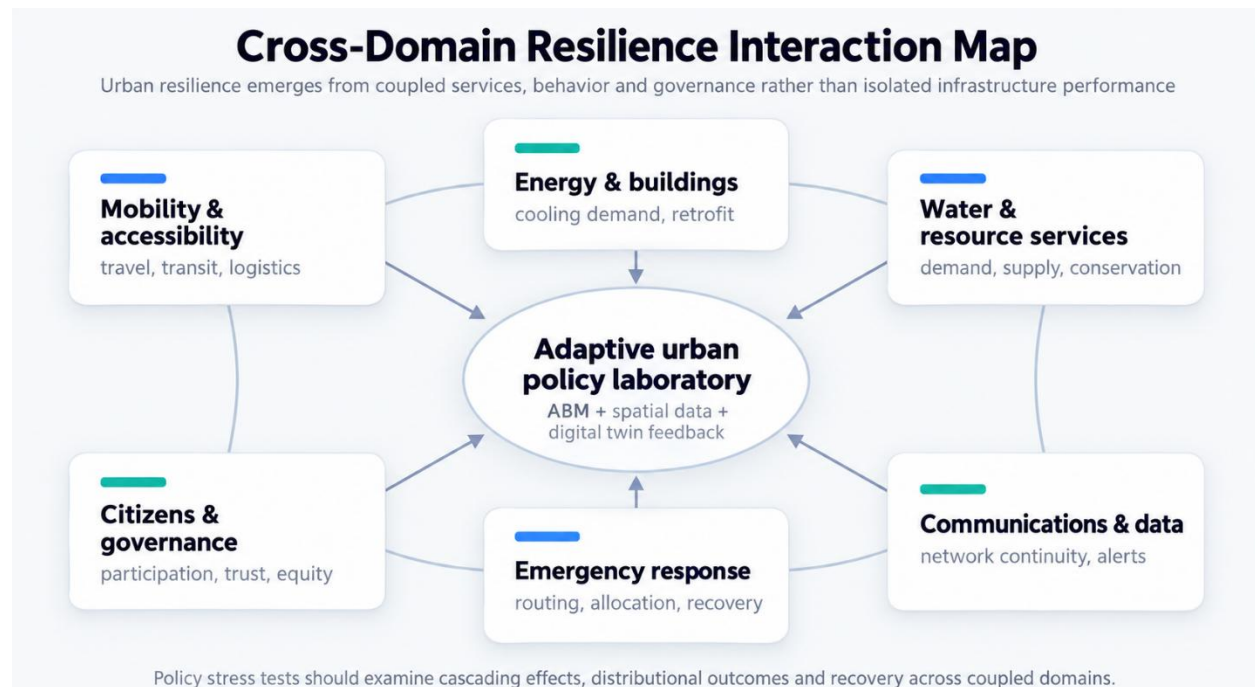


Figure 2. Cross-domain interaction map for resilience-oriented smart city planning in Saudi Arabia.

This framework conforms to the lifecycle approach of the Saudi smart city strategy while incorporating explicit behavioural experimentation. It also serves as a link between long-term planning and operational digital twins, since strategic models can be used to examine land use and technology adoption under annual or multi-year scenarios, and the operational models can adjust the short-term states on the basis of sensor data. The problem lies in governance: before simulation can be routinely used as a basis for public decisions, it is necessary to establish rules regarding shared data standards, privacy protection, model ownership, version control, and accountability for assumptions.

Another consequence is that the robustness of policy should be assessed in the face of behavioural uncertainty. Research into climate and energy issues has demonstrated that the outcomes of agent-based policies can vary depending on the assumptions made regarding preferences, social influence, technology adoption, and network structure (Castro et al., 2020). In Saudi cities, the same policy package may yield different results in different neighbourhoods since exposure to heat, household resources, digital access, travel opportunities, and levels of

institutional trust are not evenly distributed. Scenario design must therefore integrate infrastructure shocks with different behavioural responses and various implementation conditions. Instead of choosing the scenario that gives the highest modelled benefit, planners should aim to find interventions that are acceptable within a plausible range of assumptions. This approach to robustness also makes clear the role of participation: input from stakeholders can highlight missing behaviours, constraints, and distributional effects before they are incorporated into the model's logic. The outcome is a planning process that is more auditable in which uncertainty is treated as an explicit subject of discussion rather than as an invisible weakness in the modelling.

6. Research Gaps and Future Research

The main shortage is the small amount of ABM research at the city level which has been empirically calibrated and that has been specifically designed for Saudi Arabia; future studies should focus on using locally observed behavioural data rather than taking the parameters from other countries, and longitudinal mobility panels, household energy studies, investigations into heat-exposure behaviour, decisions regarding water use, and preferences with respect to public services should all greatly enhance the validity of the models.

Another gap relates to cross-domain coupling. Although smart city disruptions spread across various sectors, transport, energy, water, communications, and emergency services are typically dealt with separately. The future Saudi platforms should investigate modular, multi-domain architectures in which each subsystem is able to share its state without having to produce an unmanageable single, monolithic model. A third gap is that of social representation; equity, affordability, age, disability, household structure, digital access, and neighbourhood context should all be included in the modelling since they have a material effect on the outcomes. A fourth gap consists of model governance and here it is essential that the code be reproducible, that the assumptions be versioned, that uncertainty be reported and that independent review take place if the simulation results are to have an impact on high-stakes planning.

7. Practical, Managerial and Policy Implications

For planners the first conclusion to draw is that they should use ABM since behaviour and interaction are at the heart of the policy issue, not just because simulation technology is available. Municipal and infrastructure managers can use the method to carry out stress tests on their service networks, emergency procedures, pricing strategies and phased investments. For policymakers, ABM can make trade-offs apparent by providing distributions rather than just the citywide averages, thus showing whether a policy leads to an improvement in overall performance while at the same time worsening access or risk for certain groups.

The implementation process should start with pilot projects that are closely tied to decisions for which there is already measurable data, for example those relating to the accessibility of metro stations, district cooling demand, or the continuity of emergency routes. Having achieved success, these pilot projects can be linked together using common data standards and digital twin infrastructure. Participatory workshops should be employed in order to question existing assumptions about behaviour and to interpret the results of the scenarios. The aim must be to gain institutional learning and to carry out robust policy comparisons, not to produce a single authoritative forecast.

8. Limitations

The review is constrained by the diversity of applications of ABM and by the fact that there are only a few agent-based studies which are specific to Saudi Arabia. For this reason, it draws on evidence that can be transferred from research in other areas such as urban studies, transport, energy, resilience, and digital twins rather than asserting direct empirical evidence for each of the proposed applications in Saudi Arabia. Since the publication period in question is 2020 to 2025, it focuses on more recent methods while omitting the earlier foundational work. The framework

proposed here remains conceptual until it has been calibrated and tested using data from Saudi cities.

9. Conclusion

Agent-based modelling is a highly appropriate methodological approach for carrying out resilient and sustainable smart city planning in Saudi Arabia since it is able to link up individual and institutional decisions with infrastructure, environmental conditions, and the overall system outcomes. There is now evidence showing its value in a range of areas including transport, energy, architecture, crisis behaviour, resilience, and support for decisions made using digital twins, and the planning literature from Saudi Arabia clearly shows that there is a need for integrated, participatory, climate-aware and adaptive urban governance. The key opportunity lies in bringing these different areas together in locally calibrated policy laboratories where alternative futures can be tested before any costly interventions are finalised.

How good these models are will be less a matter of visual complexity and more a matter of having transparent rules, using credible data, undergoing behavioural validation, carrying out uncertainty analysis, and receiving scrutiny from stakeholders. When used in this careful manner, ABM can assist Saudi planners in identifying vulnerabilities, comparing different policy packages, anticipating unintended consequences, and in designing interventions which stay effective in a variety of possible futures. The most defensible role of ABM is therefore not to predict a single smart city future, but to enhance the quality of the decisions taken when facing uncertainty.

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