Research on the Collaborative Evolution Mechanism of Multiple Actors in Smart City Construction: Based on System Dynamics Simulation

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Abstract. Smart city construction helps improve urban governance and support high-quality development. This paper builds a system dynamics model from the view of multi-actor governance. The model includes technology company participation, public adoption, government promotion, and smart city development level. It also includes three policy variables: technology company subsidies, public subsidies, and regulation costs. Based on these variables, this paper simulates 27 policy scenarios. Specifically, the scenario design combines three levels of technology company subsidies Se=(2,5,8), public subsidies Sb=(3,6,9), and regulation costs Ca=(9,15,25).The results show that smart city development depends on the joint action of the government, technology companies, and the public. These actors form a positive feedback relationship. Technology company subsidies and public subsidies can improve smart city development. Their marginal effects decline when subsidy intensity rises. Regulation costs have a non-linear effect on system performance. Moderate regulation improves system coordination. Excessive regulation reduces technology innovation and policy efficiency.

Keywords: Smart city; Multi-actor collaboration; System dynamics; Fiscal subsidy; Moderate regulation.

1 Introduction

Smart city construction has become an important way to improve city governance and support high-quality urban development. Existing studies show that smart cities use key digital technologies such as the Internet of Things, cloud computing, artificial intelligence, big data communication[1]. The Internet of Things collects real-time urban data through sensors and connected devices. Cloud computing supports data storage, data processing, and service operation[2]. 5G communication provides fast and stable network services for smart transportation, smart energy, and public service systems[3]. Artificial intelligence helps urban governance through prediction, decision support, and resource allocation[4]. Open government data and smart city data governance help data sharing, platform coordination, and public trust[5]. They also need suitable rules for data

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security, privacy protection, and cooperation across sectors. Smart city construction is not only the use of technology. It is also a process of cooperation among the government, technology companies, and the public. Existing studies mainly focus on technical design, application cases, or general governance effects. Few studies examine the dynamic interaction among enterprise incentives, public subsidies, and regulation costs.

Smart city construction has clear economic logic. Smart city infrastructure and digital platforms have public good features, and many benefits are shared by the whole city. Technology companies may not invest enough by themselves, so government subsidies can reduce this problem and encourage companies to provide smart services. Public adoption has network effects. More users make the platform more valuable. In the early stage, adoption has a weak effect because there are few users. When adoption reaches a certain level, smart services spread faster and attract more companies. Regulation costs affect company participation. Proper regulation can improve data governance and public trust, but too much regulation may increase costs and weaken innovation. Regulation has a suitable range. Company participation depends on returns, subsidies, costs, and market demand. Public adoption depends on service quality, subsidies, and smart city development. Government promotion depends on development results, public demand, and governance needs.

2 System Dynamics Model and Simulation of Multi-Actor Co-Evolution

This study builds a system dynamics model for smart city co-evolution. The key variables of the model are shown in Table 1.

Table 1. Definition of Key Variables in the Smart City System Dynamics Model

Variable	Meaning
E	Technology company participation, such as the willingness to promote technologies
P	Public adoption, such as the willingness to use smart services
G	Government promotion, such as fiscal input and policy incentives
S	Overall development level of the smart city
S_e	Subsidy intensity for technology companies, which encourages technology companies to participate
S_b	Subsidy intensity for the public, which encourages users to participate
C_a	Government regulation cost
P_t,E_t,G_t	The behavior states of the public, technology companies, and the government at a given time point, namely their participation levels

2.1 Construction of the System Dynamics Model

This study uses Python to build a system dynamics simulation model for the growth stage of smart cities. The main simulation process includes the following steps.

(1) Variable Setting and Dynamic Equation Construction

The dynamic equations of the model are defined as follows:

$$\frac{dE}{dt}=\alpha_1 \cdot S_e-\beta_1 \cdot C_a+\gamma_1 \cdot P_t \quad (1)$$

$$\frac{dP}{dt}=\alpha_2 \cdot S_b+\beta_2 \cdot E_t+\gamma_2 \cdot G_t \quad (2)$$

$$\frac{dG}{dt}=\alpha_3 \cdot (P_t+E_t)-\beta_3 \cdot G_t \quad (3)$$

$$\frac{dS}{dt}=\delta \cdot \frac{E_t+P_t+G_t}{3} \quad (4)$$

The model uses a basic system dynamics structure with nonlinear policy response functions to capture weaker subsidy effects as subsidies increase, public adoption thresholds, and moderate regulation. It shows the basic feedback paths among the government, technology companies, and the public. The model does not include all complex social and technical relations in urban governance networks. In real smart city development, nonlinear effects may appear when public adoption reaches a certain level. They may also appear when technology investment becomes strong or when regulation cost becomes too high. This study discusses these effects through scenario comparison and final-state results.

(2) Setting of Scenario Parameter Combinations

The coefficient parameters are set based on previous studies and are used as baseline values in the simulation. They are kept constant to compare different policy scenarios under the same model setting. This does not mean that behavioral parameters are fixed across all cities or periods. In real smart city development, these parameters may change with city conditions, public acceptance, technology level, and policy stage. This paper focuses on the basic feedback mechanism among the government, technology companies, and the public. Future research can further test parameter calibration and sensitivity analysis for different cities and periods. The time step is 1, and the total simulation period is 50 periods. There are $3 \times 3 \times 3 = 27$ policy combinations in total. Policy Variables and Value Ranges for Smart City Construction are shown in Table 2.

Table 2. Policy Variables and Value Ranges for Smart City Construction

Variable	Meaning	Range
Sb	Public subsidy intensity	[3, 6, 9]
Se	Fiscal subsidy intensity for technology companies	[2, 5, 8]
Ca	Regulation cost	[9, 15, 25]

The coefficient parameters are set based on previous studies: $\alpha_1=0.3$, $\beta_1=0.1$, $\gamma_1=0.2$; $\alpha_2=0.25$, $\beta_2=0.3$, $\gamma_2=0.2$; $\alpha_3=0.2$, $\beta_3=0.05$, $\delta=0.4$. The initial state is set as $E_0=P_0=G_0=S_0=1.0$.

(3) Nonlinear Policy Response Functions

To make the system dynamics model easier to explain, this paper adds nonlinear policy response mechanisms to the original multi-actor interaction framework. These mechanisms describe the diminishing marginal effects of fiscal subsidies, the threshold effect of public adoption, and the moderate effect of government regulation costs. Fiscal subsidies for technology companies and the public are assumed to have positive but diminishing marginal effects. Higher subsidies can increase technology company participation and public adoption, but the added effect of each unit of subsidy becomes smaller as subsidy intensity increases. The effective incentive effect of technology company subsidies can be expressed as a logarithmic response function,

$$Fe(Se)=\ln(1+Se) \tag{5}$$

while the effective incentive effect of public subsidies can be expressed as

$$Fb(Sb)=\ln(1+Sb) \tag{6}$$

These two functions show that subsidies still work, but their effect becomes smaller as the subsidy level increases.

Public adoption may create a network effect with a threshold. At the start of smart city construction, the number of users is small, so public adoption has only a weak effect on system development. When public adoption passes a certain level, smart services spread faster and public demand gives stronger feedback to technology companies and government promotion. This effect can be shown by a sigmoid-type adoption function,

$$N(Pt)=1/[1+\exp(-\lambda p(Pt-P^*))] \tag{7}$$

where Pt denotes the public adoption level at time t, P* denotes the critical adoption threshold, and λp measures the strength of the threshold effect.

Regulation costs are assumed to have a non-linear effect on system performance. A very low level of regulation may weaken data governance, platform coordination, and public trust. A very high level of regulation may increase compliance costs, reduce technology company participation, and weaken innovation incentives. The effect of regulation is not simply positive or negative. A proper range of regulation costs can improve system coordination. This mechanism can be described by a bell-shaped regulatory coordination function:

$$R(Ca)=\exp[-\lambda r(Ca-Ca^*)^2] \tag{8}$$

where Ca* denotes the optimal regulation level and λr measures the sensitivity of system performance to deviations from the optimal regulation level. Based on the scenario setting of this paper, the medium regulation level, Ca* = 15, is regarded as the relatively optimal regulation cost.

In smart city governance, regulation costs are the costs that technology companies face when they join projects. These costs include compliance costs, approval procedures, data security rules, privacy duties, platform access standards, and reporting tasks. Moderate regulation can improve data governance, platform coordination, and public

trust. Too much regulation may raise company costs, reduce expected returns, and weaken company participation.

The smart city system changes through the interaction of different actors. Technology company participation depends on government support, company subsidies, public adoption, regulation costs, and adjustment costs. Public adoption depends on smart city development, public subsidies, company participation, and adoption costs. Government promotion depends on development results, public adoption, regulation effects, and adjustment costs. Smart city development depends on company participation, public adoption, government promotion, regulation effects, and system adjustment costs.

In practice, model parameters can be estimated with city data. Company participation can be measured by digital infrastructure investment, service providers, or project records. Public adoption can be measured by the use of smart public services, mobile government services, or smart transportation platforms. Government promotion can be measured by digital governance spending, policy support, or smart city pilot projects. Smart city development can be measured by smart city indexes, digital economy indicators, or governance performance.

2.2 Typical Scenario Simulation: Dynamic Path Analysis of System Variables

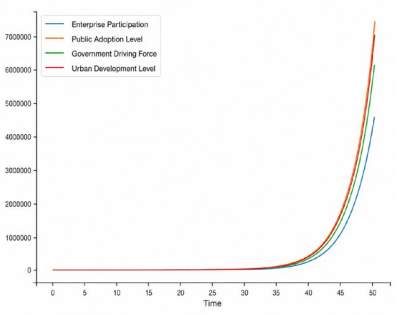


Fig. 1. Time Evolution Path of System Variables under a Typical Scenario (Se = 5, Sb = 6, Ca = 15)

This study tests the model under a typical incentive scenario with α_1=0.3,β_1=0.1,γ_1=0.2. The simulation period is 50 time steps, and the initial values are E=P=G=S=1.0. As shown in Figure 1, all variables increase over time. The growth is slow in the early stage and becomes faster after t=30. Public adoption rises first and then drives technology company participation and government promotion through positive feedback. This shows a clear three-party interaction and non-linear growth pattern.

2.3 Final-State Comparison of Policy Scenarios

The final-state smart city development level is denoted as S(t=50).To compare different policy combinations, this study records the final value of city development level S at t=50. The three policy variables are fiscal subsidy for technology companies

Se=(2,5,8), public subsidy Sb=(3,6,9), and regulation cost Ca=(9,15,25). These settings form 27 policy scenarios. Heat maps are used to show the final results under different combinations.

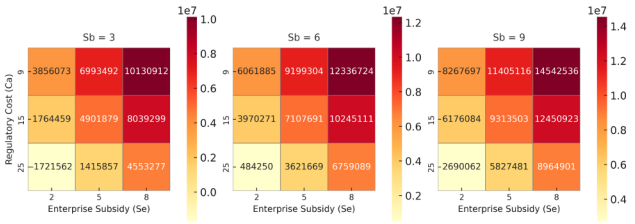


Fig. 2. Effects of Technology Company Subsidies (Se) and Regulation Cost (Ca) on System Development under Fixed Public Subsidy (Sb)

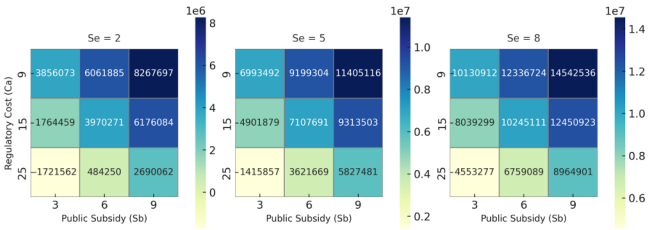


Fig. 3. Effects of Public Subsidies (Sb) and Regulation Cost (Ca) on System Development under Fixed Technology Company Subsidy (Se)

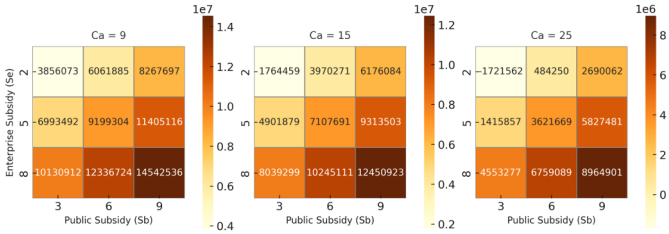


Fig. 4. Effects of Technology Company Subsidies (Se) and Public Subsidies (Sb) on System Development under Fixed Regulation Cost (Ca)

Figures 2–4 show the final system development level S(t=50) under different policy combinations. The results show that technology company subsidy Se and public subsidy Sb both have a positive effect on system development, but their marginal effects gradually decline as subsidy intensity increases. Regulation cost Ca has a nonlinear effect. The system usually performs best when Ca=15, while too low or too high regulation reduces system efficiency. This means that medium-level regulation can keep the governance structure stable and support coordination. The heat maps also show that a single subsidy policy is not enough to drive system evolution. When technology company subsidy and public subsidy are both high, and regulation cost stays at

a medium level, the system reaches the best development state. These results show that smart city policy design should focus on the joint effect of enterprise incentives, public incentives, and suitable government regulation.

3 Research Conclusions

This paper studies how different actors develop together in smart city construction. It builds a system dynamics model. The model describes the links among technology company participation, public adoption, government promotion, and smart city development level. It uses technology company subsidies, public subsidies, and regulation costs as main policy variables. The paper simulates 27 policy scenarios and compares how different policy mixes affect the development path and final level of the smart city system.

The results show that smart city development is driven by the government, technology companies, and the public. Government promotion gives policy support and system guidance. Technology companies provide digital technologies and smart services. Public adoption increases the use of smart services and strengthens market demand. These actors do not work alone. They form a positive feedback relationship during the development process. When public adoption increases, technology companies have stronger reasons to take part and the government has more reason to keep policy support.

The simulation results show that policy effects are not linear. Technology company subsidies and public subsidies can improve smart city development, but their extra effect becomes weaker when subsidy intensity keeps increasing. Simply increasing fiscal subsidies may not always bring better policy results. Regulation costs also have a nonlinear effect on system development. A very low level of regulation may weaken data governance, platform coordination, and public trust. A very high level of regulation may increase the burden on technology companies and weaken innovation incentives. The best system performance appears when subsidies for technology companies and the public are relatively strong and regulation stays at a moderate level.

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