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Towards an Urban Planning Scenario Model System—A Tool for Exploring Urban Uncertainty: A Case Study of Diaozhen, China

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Abstract: The 'Urban Interaction' project aims to develop an urban planning model system at the scale of towns or small cities consisting of three modules: growth forecast, land-use decision, and evaluation. This paper presents the framework of the model system to identify and discuss the assumptions and theoretical basis of the model system. The model system will be driven by scenario planning theory and sustainable urban development principles. It will export land-use planning based on selected urban development scenarios and urban planning theories. This paper takes Diao Town in Jinan as an example. Applying GIS spatial analysis and hierarchical analysis, this paper determines the suitability of land use and the weights of different influencing factors, combined with the land-use conflict identification model, for land-use decision-making. Finally, the assessment module verifies whether the planning scheme complies with laws and regulations to achieve an active, reactive response to uncertainty. The paper discusses the 'uncertainty' of urban planning and proposes a creative, flexible, and timely planning platform that allows planners and other participants to model and visualize their scenarios.

Keywords: urban interaction; urban model; urban uncertainty; scenario planning

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1. Introduction

The research in this paper is based on a project called "Urban Interaction", which aims to develop a dynamic urban planning modeling system to cope with uncertainty in urban planning and to support decision-making in small-town planning. Applying urban models can assist planners in quantitatively predicting urban growth, identifying urban boundaries, and making scientific land-use decisions [1]. However, while related theories and technological methods are increasing, the urban model is still a tool in the experimental stage [2]. The 'uncertainty' of urban development may be the main reason for the impact of urban modeling practice.

The research described in this paper is based on a project titled 'Urban Interaction', which aims to develop a dynamic urban planning model system. The model system will be driven by scenario planning theory and sustainable urban development principles. 'Urban Interaction', as referred to in this paper, is a coupled study of scenario planning theory and modeling methods that attempts to propose a planning methodology under the premise of an 'uncertain future' to ensure that after a perturbation occurs, the city can remain stable after a disturbance occurs. This paper identifies the 'uncertainty' in China's town planning processes. It proposes a creative, flexible, and timely planning platform that allows planners and other participants to visualize the impact of the 'uncertainty' and urban planning responses. There are three sub-modules in 'Urban Interaction', including the urban growth prediction module, the land-use decision module, and the evaluation module. After the disturbance, 'Urban Interaction' will generate corresponding response strategies based on the pre-defined scenarios. The urban growth prediction module will specify the city's growth pattern in the current state based on the objective law of the urban growth pattern, and the land-use decision module will allocate the functional use of urban land based on the LUCIS model. Finally, the evaluation module ensures that 'decisions by officials' align with the town's growth direction. Using Diaozhen, a typical small town in China, as an example, the study explores how the modeling system can respond proactively and reactively to predefined scenarios when uncertainty perturbations occur. It also verifies that the planning decisions comply with regulatory requirements and current needs and can adapt to future perturbations. However, it is worth noting that one of the key insights in 'Urban Interaction' is to pre-determine planning response scenarios based on the impacts of disturbances rather than directly linking disturbances to scenarios, and it is hoped that the applicability of scenarios will be enhanced in this way.

2. Background

2.1. Urban Modeling Method and Current Practice

The modeling approach is a research method that first creates a model based on the main features of a prototype and then studies the prototype indirectly through the model. The urban model is based on the abstraction and generalization of urban systems and quantitative mathematical descriptions of urban spatial phenomena and dynamic processes [2,3]. It is used to simulate or predict the physical form of a city or the social and economic activities in the town.

Since the 1950s, the urban model has undergone a process of rapid development, followed by a gradual decline and a subsequent revival [4]. The urban modeling approach was first proposed in the 1950s, and the spatial interaction model is representative of the early urban model. However, it lacked a reliable theoretical basis for its simulated behavior [5,6]. Due to the disconnect between theory and practice, the effectiveness of large-scale urban models was questioned in the planning field, and urban modeling research stagnated in the 1970s.

In the 1980s, the researchers began to reflect on the positioning of urban models in urban research. In re-emphasizing urban model analysis techniques, the planning community made a significant shift in understanding modeling methods—the urban model is no longer seen as a predictive tool for mechanical urban spatial change. Instead, it is used as a laboratory to simulate the evolution of urban systems. This transformation reflects the deepening of the planning community's understanding of the evolution of complex systems and the effectiveness of modeling tools. The urban model provides a virtual experimental environment that uses modern computing techniques to simulate the interactions between a large number of factors in complex systems and represents the results of the evolution of these systems at the macro level in a visible way. However, the application of urban models is still largely confined to academia, mainly because existing models often emphasize mathematical models and algorithms that oversimplify urban reality.

In the 1990s, the urban system dynamics model emerged. System dynamics (SD) is a model based on cybernetics, systems theory, and information theory and is designed to study the structural functions and dynamic behaviors of feedback systems [7]. With the development of information technology, the GIS-based model system began to appear. GIS technology can synthesize digital data representing maps and their features, as well as spatial attribute data concerning reflected features. This system, in which mapping is a primary function, combines analytical and visual capabilities, and many public and private sector-based institutions and researchers have invested in expanding the system's capabilities to apply it to models [8].

2.2. The Uncertainty of Urban Development

In the traditional planning field, there is a common belief that professional expertise to achieve well-defined goals can ensure efficient and effective management [9]. However, such plans can lead to the disappearance of unique local spatial textures and architectural cultures. Moreover, the current planning process is primarily based on the planner's prediction of the city's future development. Once the city's growth deviates from the planner's prediction due to external disturbances, it is difficult to achieve the goals of the original plan, and the city's development may be significantly affected—these potential disturbances cause the 'uncertainty' of urban development, which can lead to costly failures.

Mosadeghi et al. (2013) suggest that random uncertainty exists in the context extraction and planning process and that this occurrence is related to the decision-makers' preferences and knowledge of the MCDM (multi-criteria decision-making) process [10]. It is difficult to avoid the uncertainty of subjective judgments of decision-makers in both the process of setting criteria and weight allocation for multi-criteria decision-making. Based on its definition, uncertainty inherent in the context of natural, behavioral, social, economic, and cultural systems is random and cannot be eliminated. Erdoğan and Zwick claimed the following:

> 'Epistemic uncertainties result from imperfect or incomplete knowledge, and can be reduced through empirical efforts and high-quality data, monitoring and longer time series.' [11]

Although there are an increasing number of papers on uncertainty assessment, the planning community is still unclear on how to deal with uncertainty [11]. The most fundamental reason is that the ultimate goal of improving model accuracy conflicts with the nature of urban uncertainty. Erdoğan and Zwick compared various uncertainty analysis methods in multi-attribute modeling, particularly land-use suitability or environmental management, and analyzed the steps to generate uncertainty in model research [11]. Through the literature studies of Erdoğan and Zwick, it can be found that all existing uncertainty studies are devoted to minimizing the impact of uncertainty in the planning process by improving the accuracy of criteria standardization and weight assignment. However, by definition, uncertainty is random and cannot be predicted, which means every step could generate uncertainty. No matter how precise the criterion standardization and weight assignment process are, the possibility of uncertainty affecting decision-making still exists. Therefore, the control effect on uncertainty is limited by the methods of 'empirical efforts, high-quality data, monitoring, and longer time series'. Accepting the existence of uncertainty and optimizing the planning process according to the impact of uncertainty may be a possible choice.

Traditional planning, as a kind of static planning, has limitations regarding plan preparation, implementation, and management. Traditional planning views goals as a blueprint, a planner's prediction of future development, which is easily influenced by decision-makers preferences and is subjective in the preparation process [12]. Unlike the uncertainty in the whole planning process, static planning is challenging to adapt in a rapidly changing environment. Once the external environment changes, planning objectives may be difficult to achieve. Even after planning is completed, new challenges, such as resource constraints and policy changes, may be encountered during implementation, making it challenging to implement the original plan. In addition, management and feedback mechanisms lead to discrepancies between planning intentions and actual operations, and planning programs cannot be adjusted promptly according to the implementation situation [13]. Therefore, dynamic and variable planning becomes a key measure to face uncertainty perturbations in the future.

3. Conceptual Framework for the Urban Interaction Project

The 'Urban Interaction' project aims to develop a modular, stepwise urban planning model system based on interactive rules. This project applies scenario planning theory to control uncertainty by controlling its impact. 'Easy to understand, easy to operate, easy to modify' is the core concept of model design.

3.1. Scenario Planning

"Scenario" refers to the assumed state of a thing at a certain point in the future [9]. Many future situations may occur under different evoked conditions for the same object. Scenarios are not a future reality but a way of anticipating the future [14]. Scenario planning envisages possible future scenarios. It addresses questions that arise to help cope when something happens in the future and develops a comprehensive analysis to inform a pre-planned response [15].

Traditional planning is frequently based on the belief that applying professional expertise to achieve well-defined goals will ensure efficient and effective management. However, such plans often fail to consider the variety of local conditions or the propensity for novel situations to create extraordinary surprises [9].

Scenario planning considers the future uncertain, but the event must have a causal relationship [16]. Scenario planning starts with uncertainty research, infers uncertain factors and driving forces, summarizes several "scenarios" based on these driving forces to envisage future possible states, and formulates corresponding countermeasures [17]. Scenario planning provides a framework for decision-making in the face of uncontrollable and fundamental uncertainty and contributes to developing more resilient protection policies [9]. However, the nature of the object itself or the determined factors will occur in all "scenarios" in the same way. At the same time, the undetermined inducing conditions exist in different "situations" in various ways. Finally, a comprehensive response strategy is developed. Scenario planning aims not to provide a more accurate image of the future but to make somewhat more precise and reliable decisions [16].

The core issue of scenario planning is "scenario" predictions. These are identified as external disturbances that may arise in the future. For towns and small cities, the key uncertainties and corresponding scenarios include the following four categories: policy elements, economic elements, social elements, and environmental elements.

3.2. Model Structure

To reduce the complexity of the model, the system needs to avoid excessive integration. The entire model calculation process, from context extraction to result in export, consists of three independent modules: urban growth prediction, land-use decision, and evaluation.

The first module, the urban growth prediction module, is concerned with future urban forms. The prototype model applied is the mathematical model. The export result of the urban growth prediction module is based on the statistical analysis of historical data. It will take into account both the physical features of the object and the social and economic characteristics of the object. This module predicts the city's future development and identifies the urban growth boundary.

The second module, the land-use decision module, aims to identify the potential land-use conflict and allocate future land use. The prototype model applied is the LUCIS model. The export result of the land-use decision module is based on local regulations and previous research on land-use suitability analysis. The land-use decision module must prepare multiple sets of different parameter weights corresponding to the possible scenario.

The third module, the evaluation module, is targeted at developing an urban planning evaluation system. It consists of a multiple MCD matrix, which evaluates the output of the urban growth prediction module and the land-use decision module based on the goal system of the entire model system and provides feedback to these modules.

The Figure 1 below explains the structure of the entire model system.

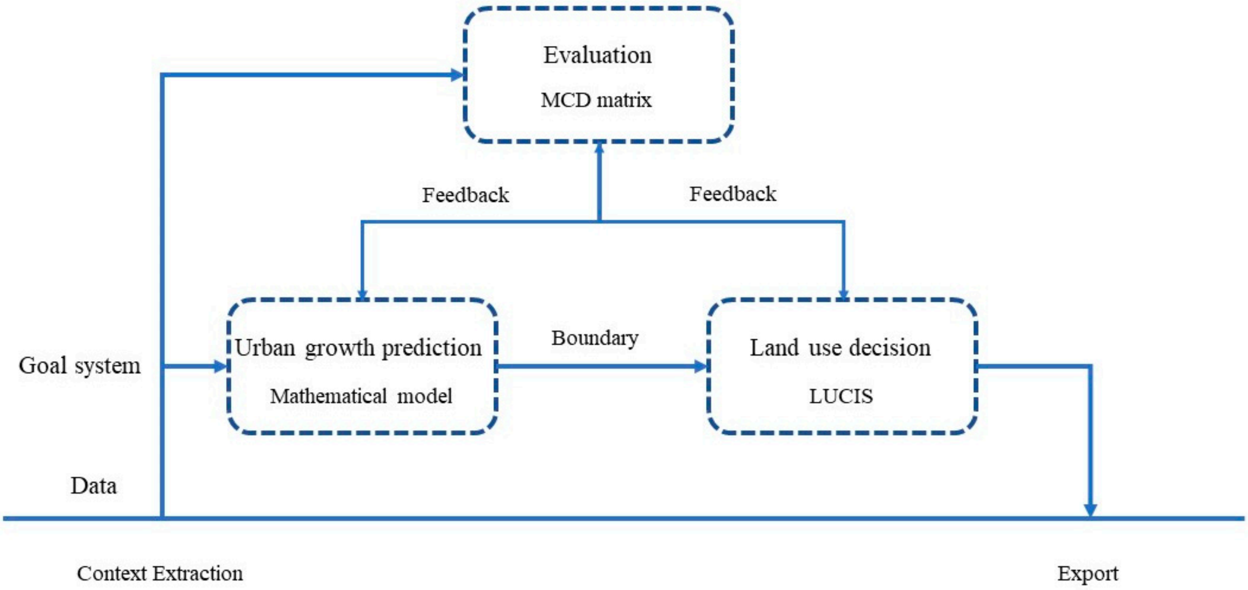


Figure 1. Basic conceptual model.

3.2.1. Internal Interaction

In the holistic model system, each module operates independently—the internal interaction rules and the scenario selection combine all the modules.

The following Figure 2 explains the details of the internal interaction of all the sub-models and parameters. The "goal system" is the foundation of the growth ratio identification, the land-use suitability analysis, and the evaluation matrix. All three modules share the same "goal system" to ensure these sub-models operate under unified values. The internal interaction system is established based on the goal system because the goal system can effectively connect planners, participants, and model systems. For planners, the goal system can be transformed into land-use suitability analysis results, and it can directly guide planners in making land-use decisions. For participants who lack planning expertise, the goal system can be presented in a natural language form. At the same time, the goal system for the model system can be directly translated into parameter weights through the AHP method, and the weight can be used in the model calculation. In today's planning context, which emphasizes the integration of planning formulation, implementation, and management, it is not easy to fully use data resources in the original time-based planning management mode. The study of the model-based dynamic planning system is significant for exemplary planning management and the precise placement of spatial policies.

"Scenario system" is the leading platform for implementing the interaction of the internal parameters within the model. The internal interaction between all the parameters is achieved through scenario selection. For the urban growth prediction module, the scenario system can correct the growth ratio based on the land-use policy or the characteristics of the production activities of the corresponding scenario. For the land-use decision module, the scenario system mainly affects the weight of different land-use suitability criteria and the priority sequence of the land-use allocation process. For the assessment module, the scenario system determines the MCD matrix criteria for each scenario. The evaluation module then performs a 'scenario test' on the results of each scenario based on the urban resilience theory, which refers to the ability of a city to remain stable and return to its original state in the face of uncertainties and perturbations [18]. Urban resilience theory refers to the ability of cities to maintain stability and recover in the face of uncertainty and perturbation. In the assessment module, urban resilience theory is applied to determine when a scenario is in effect. The scenarios are based on the towns' resilience, i.e., their ability to resist disturbances. When the potential impact of a disturbance exceeds the city's carrying capacity, external intellectual regulation is needed to ensure the stability of urban development. Therefore, with the iterative feedback of the assessment module, the resilience and flexibility of the entire plan can be better realized to improve urban resilience.

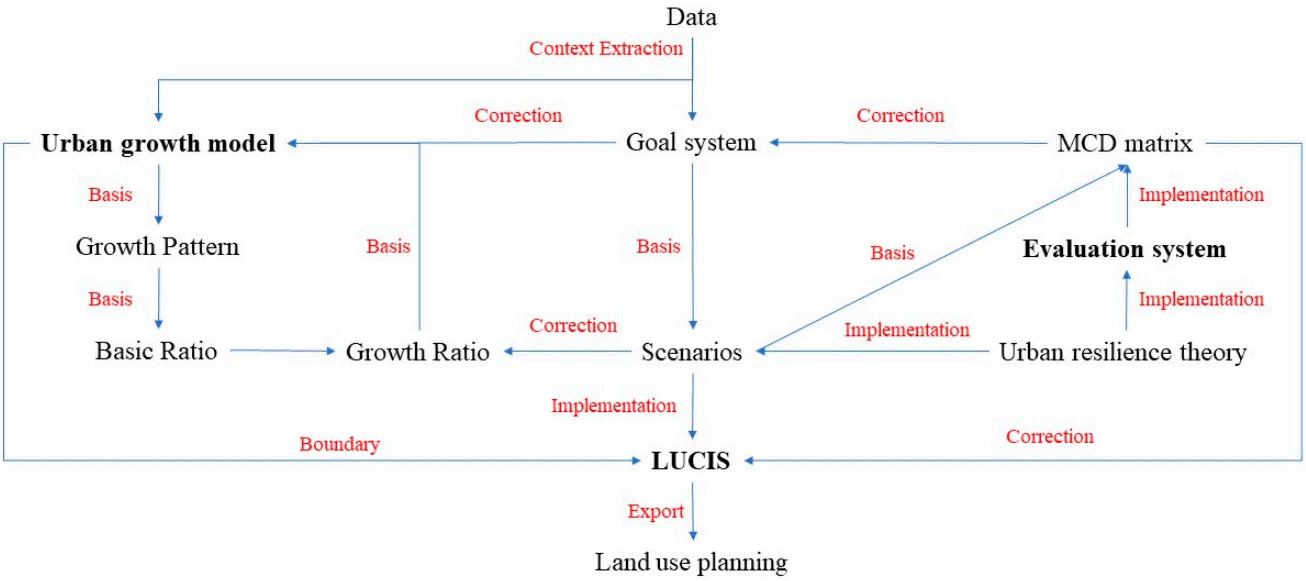


Figure 2. Internal interaction framework of the model.

3.2.2. Evaluation System

In addition to the mathematical and system dynamic models, a complete model system also requires a plan evaluation module to analyze the results of the model calculations and ultimately select the optimal results.

Although many existing evaluation tools exist, only a few are still active and applicable to their specific purposes [19]. Therefore, the evaluation module of the model needs to be designed concerning local urban planning evaluation systems. There are three different tests in the evaluation system for the three different ontologies of the model system.

'Regulation test' is mainly designed so the output can satisfy legal regulations and regional requirements.

'Result test' is mainly designed so the output can satisfy the current needs of the object.

The scenario test mainly ensures the object's ability to cope with uncertain disturbances.

3.3. Model Calculation Procedure

3.3.1. Pre-Planning Stage

The pre-planning stage is mainly to collect the data and provide the basis for the model's calculation, which includes primarily collating the spatial planning and the economic development planning related to the objective, obtaining the relevant information of the urban development goal in the planning documents, focusing on the bottom lines in the spatial plans; constructing the public participation platform, collecting the public opinions on participation, including the conscious or unconscious participation, focusing on the public's demand for the housing quality; collecting historical data on urban development, including the data of urban growth data and population growth data; and collecting the current land-use layout information of urban developed areas, including the industrial distribution, road network, and infrastructures.

Based on the collected data, construct the overall objective of urban development and clarify the priority sequence in the city's "production, residential, and recreational" construction. Under the guidance of the overall objectives of urban development, a sub-objective system was formulated for "production, residential, and recreational" construction. In the planning practice, it can be added or modified according to the actual situation.

According to the collected data, weight is assigned to each sub-objective in proportion. The method of weight allocation is the analytic hierarchy process. The production sub-objective should be formulated for the types of industries that already exist or may exist in the future in the objective. The opinions of the municipal management administration should be put in the first place, the opinions of the higher management administration in the second place, and the opinions of the citizens should also be taken into consideration, with a weight ratio of 5:3:2. In the residential sub-objective system, the opinions of the citizens should be given the highest priority, the opinions of the municipal management administration the second priority, and the opinion of the higher management administration is taken into account, with a weight ratio of 5:3:2. In the recreational sub-objective system, the opinions of the higher management administration should be given the highest priority, followed by the opinions of the citizens, while taking into account the opinions of the municipal management administration with a weight ratio of 5:3:2. Based on the above steps, the opinions of all stakeholders are finally collected and analyzed through an analytic hierarchy process, and the pre-set objective system is sorted out to obtain the weight of each sub-objective in the final decisions on land use.

After obtaining the objective system in the basic scenario, possible external disturbances are predicted according to the overall objectives of urban development and combined with the stage of urban development and the industrial orientation of the region. The external disturbances are classified and summarized into four types: social, economic, environmental, and policy. Social disturbance mainly indicates changes in the population, including changes in the number of people and changes in the population's age structure, which is often adopted to deal with disturbances like village mergers, population loss, and an aging population. Economic disturbance mainly indicates changes in the priorities of different industries in urban production activities, which is often adopted to deal with disturbances like industrial chain adjustment of the region, urban industrial structure adjustment, and urban industrial adjustment of development focus. Environmental disturbance mainly indicates changes in the water and air environments, which are often adopted to deal with disturbances like water and air pollution. The policy disturbance includes changes in regional policies and urban development strategies. Each scenario requires establishing a corresponding objective system weight and scenario selection baseline, and parameters and standards for scenario detection are formulated based on different scenarios (Table 1).

Table 1. Quantitative indicators for scenarios based on the literature review.

Classification of Disturbances	Quantitative Indicators of Disturbance Impact Factors	Number of Articles in the Literature	Origin	Response Scenarios
social disturbances	Changes in the size of the population, changes in the age structure of the population	16	[20–24]	village mergers, population loss, and an aging population
economic disturbances	the changes in the priorities of different industries in urban production activities	12	[25–28]	industrial chain adjustment of the region, urban industrial structure adjustment, and urban industrial adjustment of development focus
environmental disturbances	Changes in the water environment and changes in the air environment	7	[29–31]	water pollution and air pollution
policy disturbances	——	5	[21]	changes in regional policies and changes in urban development strategies

3.3.2. Planning Stage

The planning design stage mainly includes the urban growth prediction module and the urban land-use decision module. The urban growth prediction module conducts a logistic regression analysis with the historical data collected during the planning research stage to clarify the influencing factors and the priorities among the factors in urban growth. On this basis, suitability analysis is adopted to investigate all units within the scope of the urban developable land. The pre-set influencing factors include the following (Table 2):

- Using statistical geographical factors: slope and the distance from the coast;
- Ecological factors: forests and wetlands;
- Population factors: population density;
- Economic factors: the existing city, the distance from the central business district, the distance from the central industrial area, and the distance from the existing city;
- Policy factors: attraction of protected areas and city clusters;
- Cultural factors: historical and cultural reserves;
- Infrastructure factors: distance from highways, distance from main roads, distance from hubs, road density, distance from shoreline.

Table 2. Spatial index extraction based on a literature review.

Classification of Influencing Factors	Number of Articles in the Literature	Origin	Extraction of Evaluation Indicators
Geographical factors	12	[32–34]	slope and the distance from the coast
Ecological factors	8	[35,36]	forests and wetlands
Population factors	3	[37]	population density
Economic factors	7	[38,39]	the existing city, the distance from the central business district, the distance from the central industrial area, and the distance from the existing city
Policy factors	2	[40,41]	attraction of protected areas and city clusters
Cultural factors	2	[37,42]	historical and cultural reserves
Infrastructure factors	5	[43,44]	distance from highways, distance from main roads, distance from hubs, road density, distance from shoreline

Using statistical analysis results, combined with the objective system, predict the future growth trend of urban and rural areas. Experts, the city, and the higher administration managers mainly control urban growth's objectives. Its effect could be reflected by selecting and ranking all the influencing factors, and then the weights are obtained through the analytic hierarchy process. The result of logistic regression indicates the passive adaptation of the urban under the current conditions, and the objective system shows the participants' will in urban planning. Therefore, the prediction result of each one accounts for 50% of the final result.

Urban growth prediction combined with objective control and statistical analysis is mainly used to indicate the possibility of urbanization of all the land around the city. Based on the above analysis, it is necessary to obtain the urban growth boundaries according to the growth ratio. The growth ratio is the ratio of urban construction area to regional population growth. The calculation formula is as follows:

$$r = [(A1 - A0)/A0]/[(P1 - P0/P0)]$$

In the formula, A1 represents the area after urban growth, A0 represents the area before urban growth, P1 represents the population before urban development, and P0 represents the population after urban growth (source: [45]).

When applying the basic scenario, the growth ratio takes the general ratio of urban growth, which is 5:1. In the scenario of the aging population, environmental pollution, and service industry development, the ability of and the will for urban expansion decline, and urban growth is restrained. The growth ratio will fall by 10% when each scenario appears. In the intelligent growth scenario with policy disturbances, the policy limits urban development, urban expansion is under severe control, and the growth ratio will drop by

20%. In population rejuvenation, industrial development, and real estate development, the ability and will for urban expansion increase. The growth ratio will increase by 10% when each of the above scenarios appears, and in the rapid growth scenario with policy disturbances, the growth ratio increases by 20%. The specific calculation process is shown in the Figure 3 below:

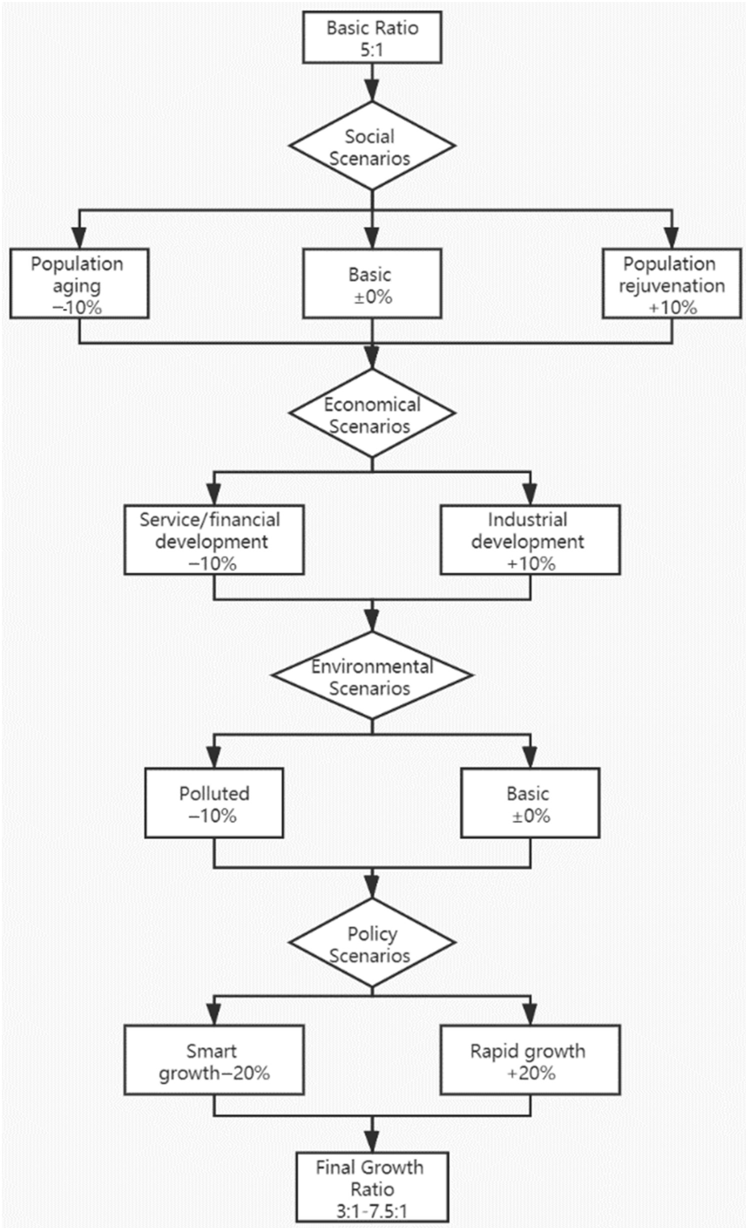


Figure 3. The growth ratio identification process.

The urban land-use decision module needs to use the output of the urban growth prediction module. Within urban growth boundaries, the land suitability analysis is adopted to investigate each type of land in the city that needs to participate in land-use decision-making. In the suitability analysis, each factor's evaluation classification standards correlate to the laws and regulations. For example, the factor evaluation classification standard is "Sub-objective 1.1.1: Identify urban land units with the slope suitable for residential use". According to the relevant requirements of the Code for Vertical Planning on Urban Field, units with a slope of 0–0.3% need specific engineering measures to meet drainage requirements; units with a hill of 0.3–0.8% need no engineering measures to level the land; units with a mountain of 8–25% can be developed as residential land; units with a slope greater than 25% should not be developed as residential land. A score of 9 indicates an area with a highly suitable slope, while 1 indicates an inappropriate one. The slope suitability value is shown below (Table 3).

Table 3. Slope suitability value.

Suitability Value	Slope	Note
9	0.3–0.8%	
7	0–0.3%; 0.8–15%	
5	15–25%	
1	>25%	Against regulations

For factors lacking clear related laws and regulations as their basis, the evaluation standard will focus on the people's behavioral characteristics. For example, the factor evaluation classification standard of "identify urban land units close to open waters or public green spaces" needs to take residents' walking willingness and walking speed as indicators to obtain the value of the land's suitability for use (Table 4).

Table 4. Proximity to open waters or public green spaces suitability value.

Suitability Value	Distance	Note
9	0–80 M	1-min walk
8	80 M–240 M	3-min walk
7	240 M–400 M	5-min walk
6	400 M–800 M	10-min walk
3	800 M–1200 M	15-min walk
1	1200 M–Max	More than 15-min walk

According to the land-use suitability analysis, for each type of land use, all construction land in urban areas is classified into three categories: land suitable for construction, land capable of construction, and land unsuitable for construction. According to the suitability of all construction land in urban areas for various land uses, land conflicts in urban areas have been identified. Each urban land unit has three different suitability values for three types of land, and according to different suitability values, urban land can be divided into the following categories:

- Existing Residential Land;
- Existing Production Land;
- Existing Recreational Land;
- Preferred Land for Future Residential Land;
- Preferred Land for future Recreational Land;
- Preferred Land for Future Production Land;
- Land Where Future Recreational Land and Residential Land May Conflict;
- Land Where Future Recreational Land and Production Land May Conflict;
- Land Where Future Residential Land and Production Land May Conflict;
- Areas Where Future Recreational Areas, Residential Areas, and Production Areas May Conflict.

We allocate land use based on the priorities identified in the urban development objectives. The principle of handling land conflicts is the general aim of urban development. For example, if the overall purpose of a city's growth is to "prioritize the improvement of the living environment, followed by the development of the industrial economy and the consideration of ecological protection", then the corresponding land conflict handling steps are as follows:

1. In the land suitability analysis, land units with the highest score for residential suitability and no conflict are classified as residential land.
2. Estimating the area of residential land required based on population prediction. If the land area in the previous step is inadequate, choose a land unit that conflicts with residential land and classify it as residential land.
3. Land units with the highest production land suitability scores and no conflicts are classified as production land.
4. Land units with the highest recreational land suitability scores and no conflicts are classified as recreational land.
5. According to the population prediction and employment indicators of the relevant production categories, assess the area of production land required, select the land units that conflict with production, and classify it as production land.
6. Classify the remaining land as recreational land.

The evaluation module includes the regulations test module, the result test module, and the scenario test module. Each module has three elements: evaluation principles, factors, and feedback directions. The regulation test module ensures that the output of the model meets the requirements of master planning and other regulations. The evaluation factor is the city's growth boundary, the type of land explicitly controlled by master planning, etc. The feedback direction is the urban growth ratio and growth weight. The result test module ensures that the model's output meets the current need for the objective. Evaluation factors include production land area, residential land area, green space area, etc. The feedback direction is suitability analysis weight and objective system. The scenario test module is used to ensure that the model's output can make corresponding adjustments to the disturbance after the corresponding scenario is developed. The evaluation factors include social adjustment methods, industrial adjustment methods, environmental adjustment methods, and policy adjustment methods. It needs to be formulated according to the objective's development status. Evaluation factors include the production land area, residential land area, green space area, etc.

3.3.3. Planning Implementation

After the plan passes the evaluation process, it enters the stage of planning implementation, which mainly corresponds to the parts of scenario detection, scenario selection, and scenario detection in the model. Once a specific parameter breaks the pre-set baseline due to the influence of external disturbances during the city's development, the scenario detection module will immediately reflect it to the scenario selection module, and the corresponding module will be selected and reflected in the planning result. The specific calculation process of the model is shown in the Figure 4 below:

Based on the research on urban resilience, this thesis establishes a system dynamics model, which transforms the prediction of the response of small towns to uncertain external perturbations into the simulation of rent-seeking behaviors of various types of subjects in small towns under different conditions and selects a total of 56 factors affecting the growth of land use and land-use decision-making through the literature review, so that the planner can formulate the relevant scenario identification baseline based on the specific conditions and development objectives of the target small towns, and control the negative impacts of the perturbations through the diagnosis and identification of perturbations beforehand. Based on the specific situation and development objectives of the target small towns, the planner can formulate the relevant scenario identification baseline and, through the diagnosis and identification of perturbations, control the negative impacts of the perturbations in advance through the planning and regulation methods.

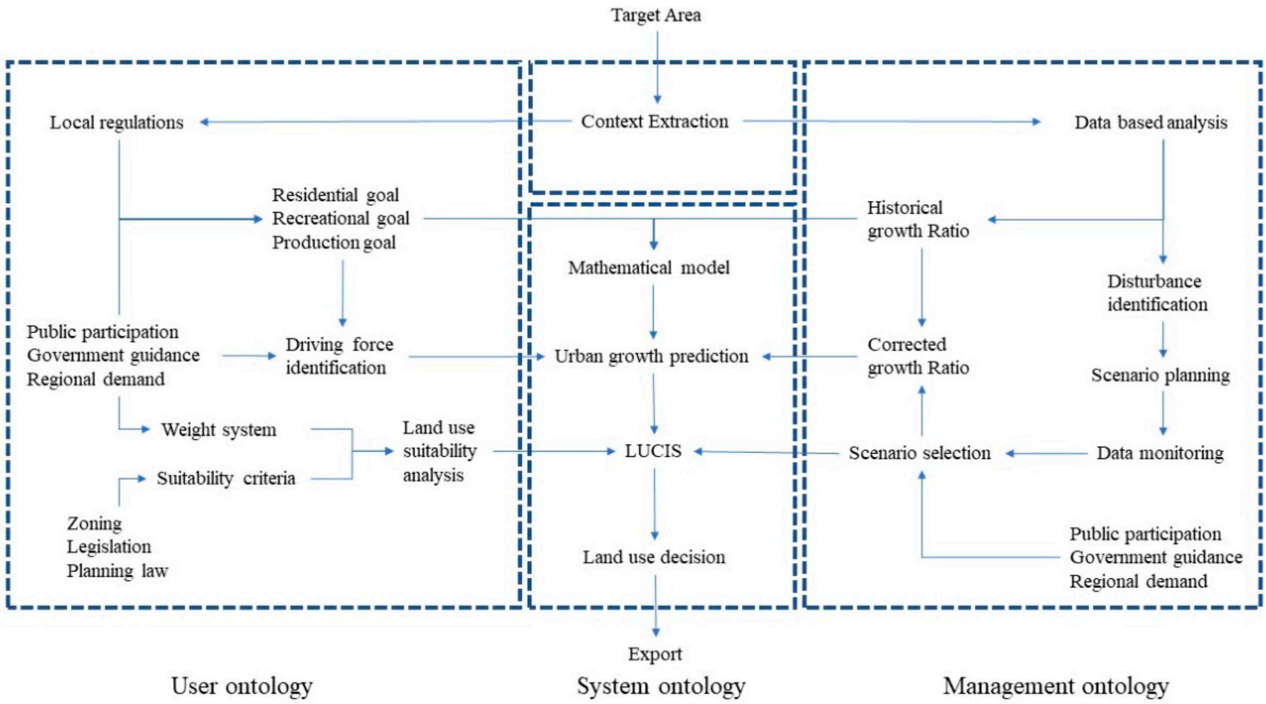


Figure 4. Calculation process of the model.

4. Case Study

4.1. Research Area

China's small towns are proper research objects for urban modeling research. Firstly, China's small-town demand for redevelopment and improvement is significant. Meanwhile, China's small towns play an irreplaceable role in forming the urban agglomeration system and driving rural development. Due to the urban agglomeration system in China, small towns are regarded as the middle link of the regional industrial chain, serving the central city. Therefore, the production function in China's small towns is clear and straightforward, which is proper for current urban modeling practice. Diaozhen belongs to Zhangqiu District, Jinan City, Shandong Province. As of 2017, it had a permanent resident population of 123,814. Diaozhen takes the regional center city of Jinan as the core area and Zhangqiu as the supporting area, which will be instrumental for the formation of linkages and cooperation with the surrounding towns.

Among them, data on the current land use situation in Diao Township are mainly derived from the Third Land Survey conducted by the Bureau of Natural Resources. The third land research is the basis for the state to formulate central strategic planning and economic and social development policies. These data contain the type, area, land quality, and other data of various kinds of secondary land, including arable land, construction land, and ecological function land. Data from the third land research is saved in the form of a GIS database, which is filtered according to fields and then entered into the framework of 'Urban Interaction' in this paper.

4.2. Growth Prediction

The Figure 5 shows the growth boundary comparison of Diaozhen applying different scenarios, and the corresponding growth ratios are 7.5:1, 5:1, and 3:1, respectively. Among them, 5:1 is the default growth ratio obtained in combination with China's land management regulations and the sustainable development principle; 7.5:1 is the maximum growth ratio, which is the fastest growth mode of small-town land under the premise that the population age structure, industrial type, environmental quality, and regional policy are all allowed. The maximum limit of the growth ratio is set to control the growth ratio of small towns so that they do not exceed their service and management capacity and also to ensure the reasonable distribution of land rent; 3:1 is the minimum value of the growth ratio. It is a growth mode in which small towns meet the requirements of regional development on the premise that population age structure, industry type, environmental quality, and regional policies are all limited. The minimum limit of growth ratio is designed to ensure the sustainable growth of small towns, maximize the development of their resources, promote the rational distribution of regional industries and populations, and ensure the standard construction of the regional urbanization chain.

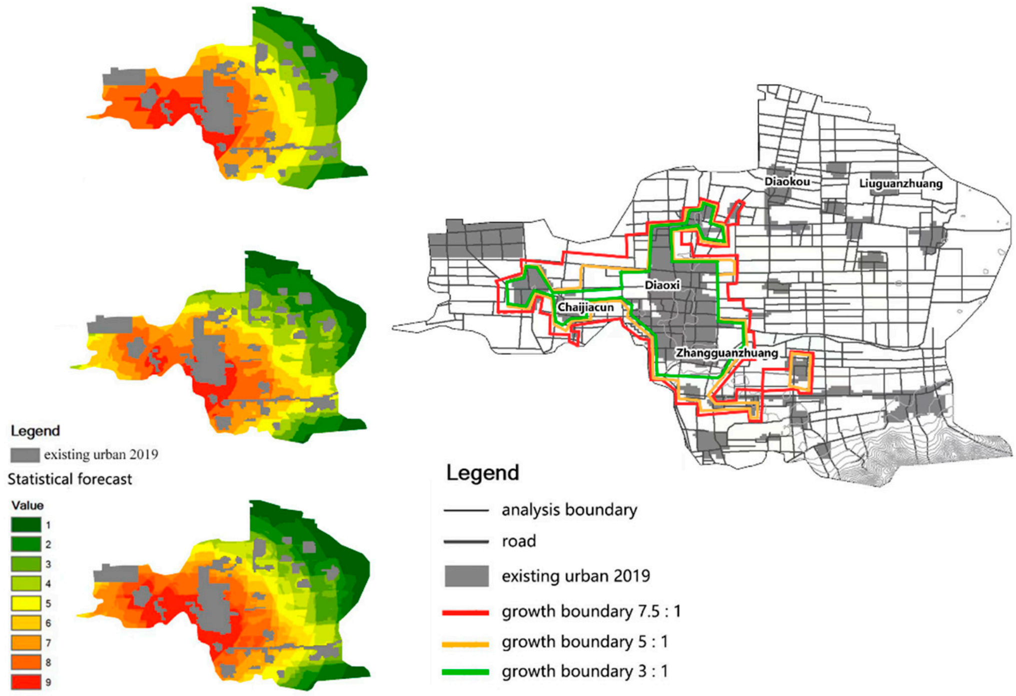


Figure 5. Growth prediction of Diaozhen applying different scenarios.

4.3. Land-Use Suitability

Based on the land-use suitability criteria proposed in the previous section, the single-factor suitability of all land-use units in the target small-town analysis scope can be analyzed. Using GIS10.6 buffer analysis, single-factor site suitability evaluations were generated separately in the analysis process. In this case, Euclidean distance was used for buffer analysis, and various relevant laws and regulations were used as reclassification criteria. The suitability of a single factor of each land-use unit is uniformly expressed by a suitability value of one to nine. One means very unsuitable for development, and nine means very suitable for development, for the sake of the intuitive expression and comparison of the suitability of different factors as well as the evaluation of overall land suitability. Taking residential land use as an example, the Figure 6 below shows the results of the single-factor suitability analysis of residential land use.

4.4. Identifying Potential Conflicts of Land-Use

According to the single-factor suitability in the previous section and the land-use goal system, the suitability evaluation of a single land-use type for each unit can be completed. The method for determining the weight of the adaptive superposition of a single factor is AHP. In the AHP analysis process, each factor's priority order is described in Section 3.3.1. Because each factor has a different priority order in other situations, it must be discussed separately.

Based on the single-factor suitability analysis result, using the spatial overlay analysis of GIS, the singles can be weighted to reflect the impact of different scenarios on land use. The Figure 7 below show the suitability evaluation of each land-use type applying to every scenario.

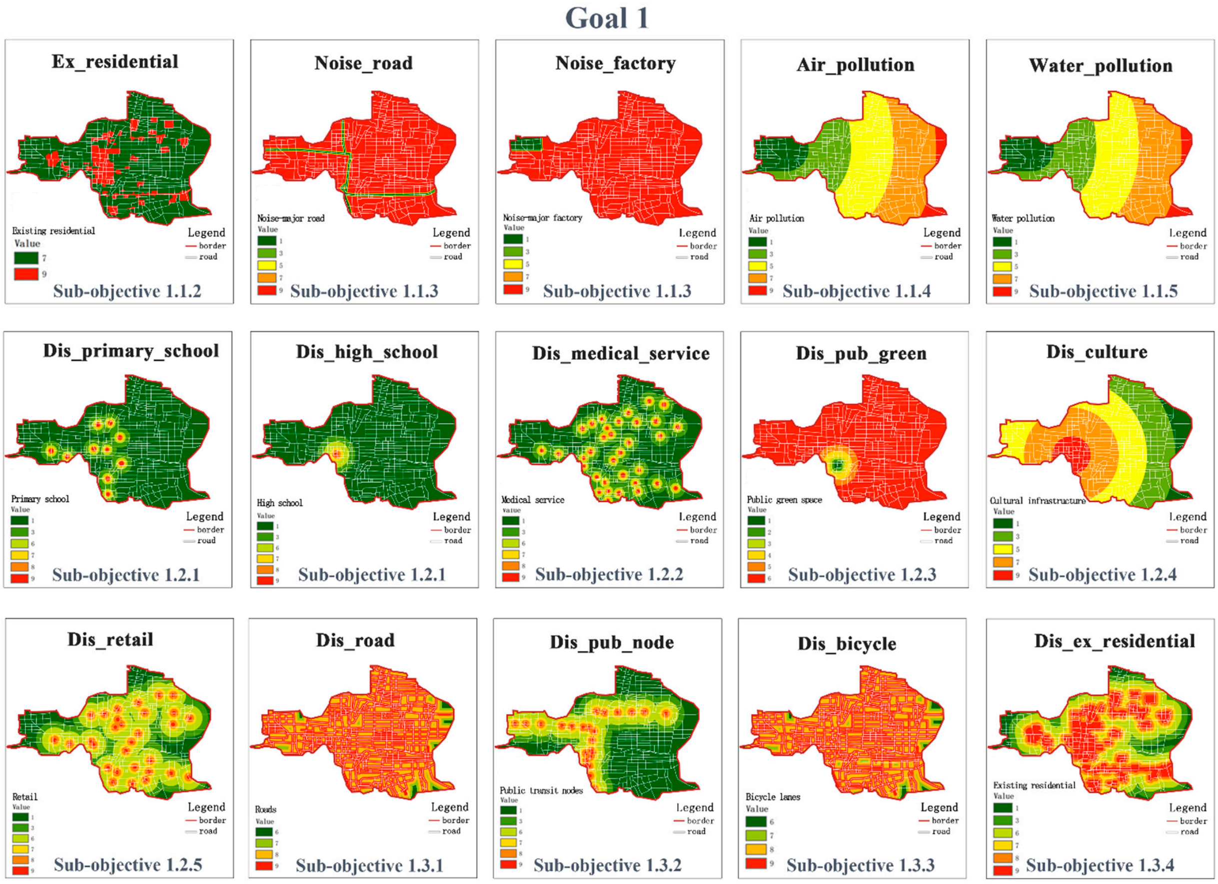


Figure 6. Single-factor suitability analysis result f of residential land use.

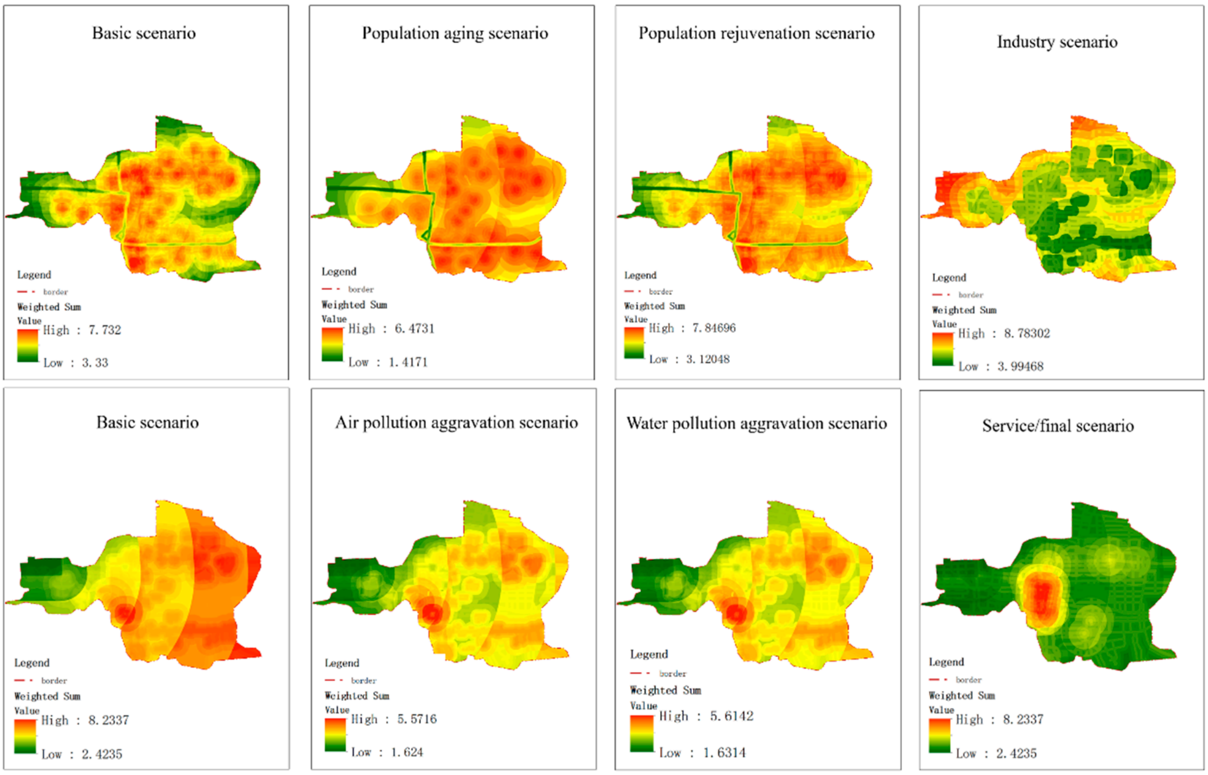


Figure 7. Land-use suitability analysis results applying different scenarios.

Based on the suitability analysis of each single land-use type, the Figure 8 below show the land-use conflict identification analysis result of Diaozhen applying a basic social scenario, an industrial economic scenario, a basic environmental scenario, and a rapid growth regional linkage strengthening scenario. As a result, each type of land-use conflict has a code. The percentile number represents recreational suitability, the tenth number represents residential suitability, and the single-digit number represents production suitability. The land conflict results will also change for different land-use scenarios. The following Figure 8 shows the results of land-use conflict identification applying the basic population scenario, industrial production scenario, basic environmental scenario, rapid growth scenario, and regional linkage strengthening policy scenario.

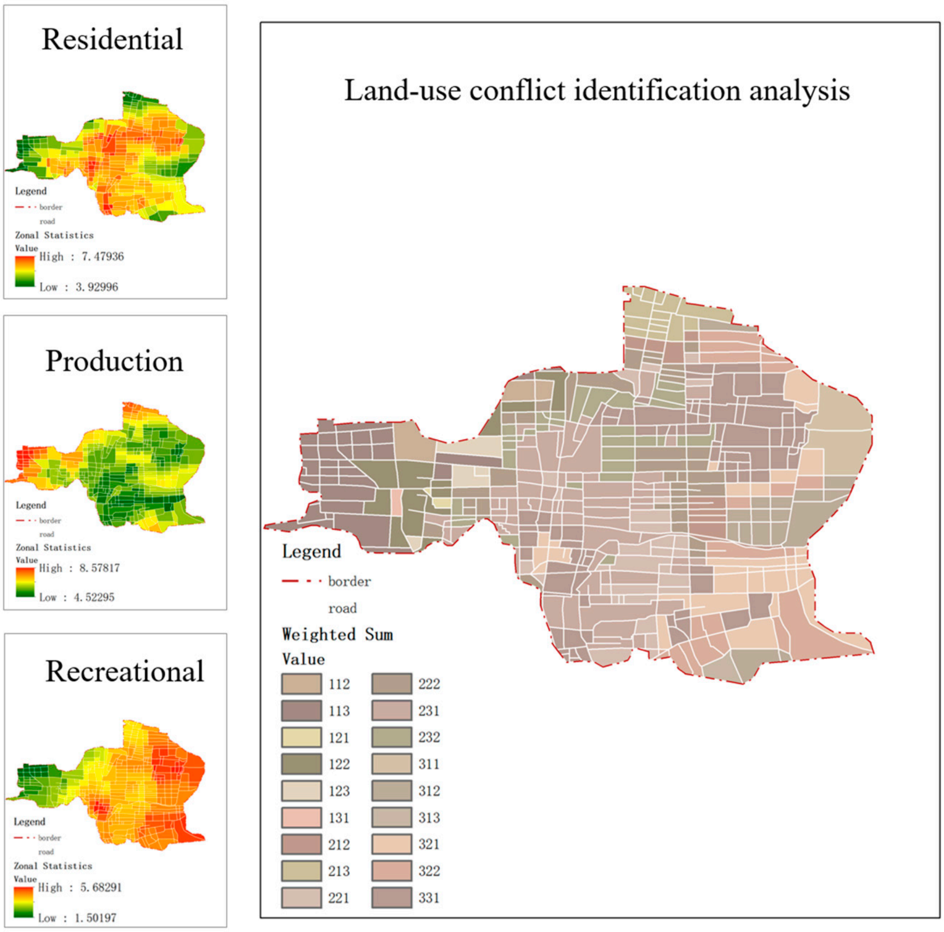


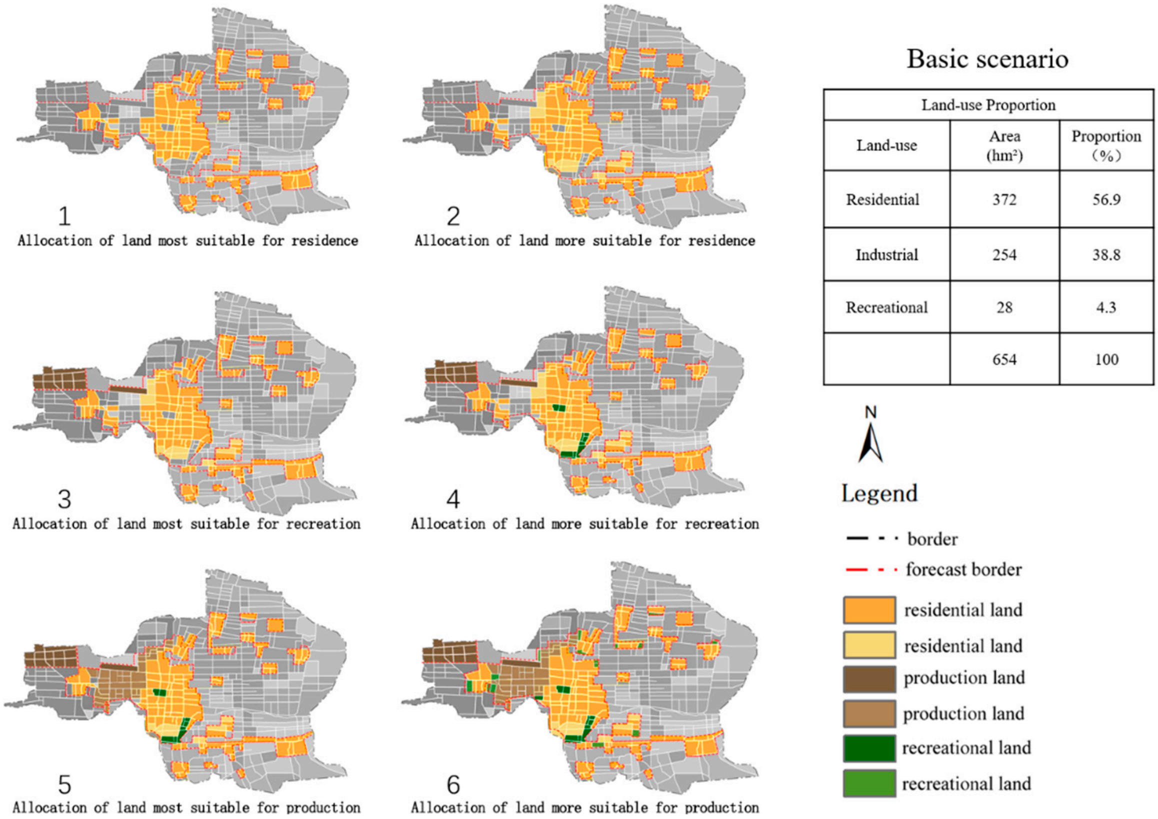
Figure 8. Land-use conflict identification analysis.

4.5. Allocating Future Land Use

According to the priority order of different land types described in the previous article, the Figure 9 below show the land-use allocation process in industrial small towns, where shades of gray represent site conflicts that exist on the site.

4.6. Scenario Detection and Application

To deal with the uncertainty of urban development and ensure the effectiveness of planning results, the model needs to respond to scenarios and update planning results. According to the possible effects of different types of disturbances in the city, the disturbances are divided into four categories. A corresponding monitoring baseline is set for scenario application and scenario evaluation.



Land-use Proportion		
Land-use	Area (hm^2)	Proportion (%)
Residential	372	56.9
Industrial	254	38.8
Recreational	28	4.3
	654	100

Figure 9. Land-use allocation process in industrial small towns.

4.6.1. Social Scenario

Scenario-related indicators: The travel patterns of residents of different ages are pretty different, and their choice of residence is also different. According to the population's age structure, it can provide other services for various age groups in small towns. Therefore, the evaluation of population age structure is used as the primary indicator for land-use decisions. The proportion of the aging population and youth population is related to the "population aging scenario" and "population rejuvenation scenario", respectively, and together with the "basic scenario", they affect the decision of urban land use. For each 1% increase in the population of the elderly or school-age children aged 1–14 accounting for the total population, the weight of the corresponding "population aging scenario" or "population rejuvenation scenario" will increase by 5%.

4.6.2. Economic Scenario

Scenario-related indicators: Due to the system of urban agglomeration development, small towns, as a part of regional coordinated development, participate in the production of regional industrial chains. To some extent, this economic development mode restricts the economic structure of small towns, resulting in a simple industrial structure, a low ability to resist external interference, and urban solid disaster resistance. Therefore, the detection of the employment ratio is conducive to the effective monitoring of the economic development trend of small towns by small-town managers and planners and is of great significance to the long-term stable development of small towns. According to the literature research, the employment multiplier corresponding to the industry and service industry in China is between 0.4 and 0.6. Therefore, when the service industry and industrial employment in small towns are higher than 0.6, the service industry scenario will take effect. According to the research of Wang et al. (2015) [46], as a highly developed Chinese city, the employment multiplier of industrial jobs in Shanghai is 1.5. Therefore, for any small town in China, the employment multiplier of the industry is between 0.6 and 1.5. For every 0.1 increase in the employment multiplier, the "service industry scenario" weight will increase by 11.11%.

4.6.3. Environmental Scenario

Scenario-related indicators: The aim of setting up environmental evaluation is to enable the land-use decisions of the target small towns to make corresponding adjustments based on changes in ecological quality. Air and water are the main aspects of evaluating a town's overall living environment. In urban development, the air and water environment indicators will eventually reflect a series of environmental problems caused by population and industry clusters.

According to the "Ambient Air Quality Standard", the number of days with good air quality in a city can be calculated for air pollution scenarios. The air pollution scenario takes effect when the number of days with good air quality is less than 80%. For every 1% increase in pollution days, the weight of the "air pollution aggravation scenario" will increase by 1.25%.

For the water pollution scenario, when the water quality compliance rate of urban water functional areas is less than 70% or a Class V water body appears, the water pollution scenario takes effect. Due to the diffusion and sustainability of water pollution, the weight of the "water pollution aggravation scenario" in all downstream areas will be increased to 100% before the pollution source is treated.

4.6.4. Policy Scenario

Due to the characteristics of policy disturbance, the scenario-related indicators of policy disturbance are identified by specific targets in the policy document. Since the policy's content is too complex to quantify directly, the actual effect of the policy needs to be predicted. Compared to other perturbations, policy perturbations usually directly impose rigid constraints on the construction of small towns. After excluding policy impacts that can be described in social, economic, and environmental scenarios, relevant policies that significantly impact small-town development can be categorized into the following four groups:

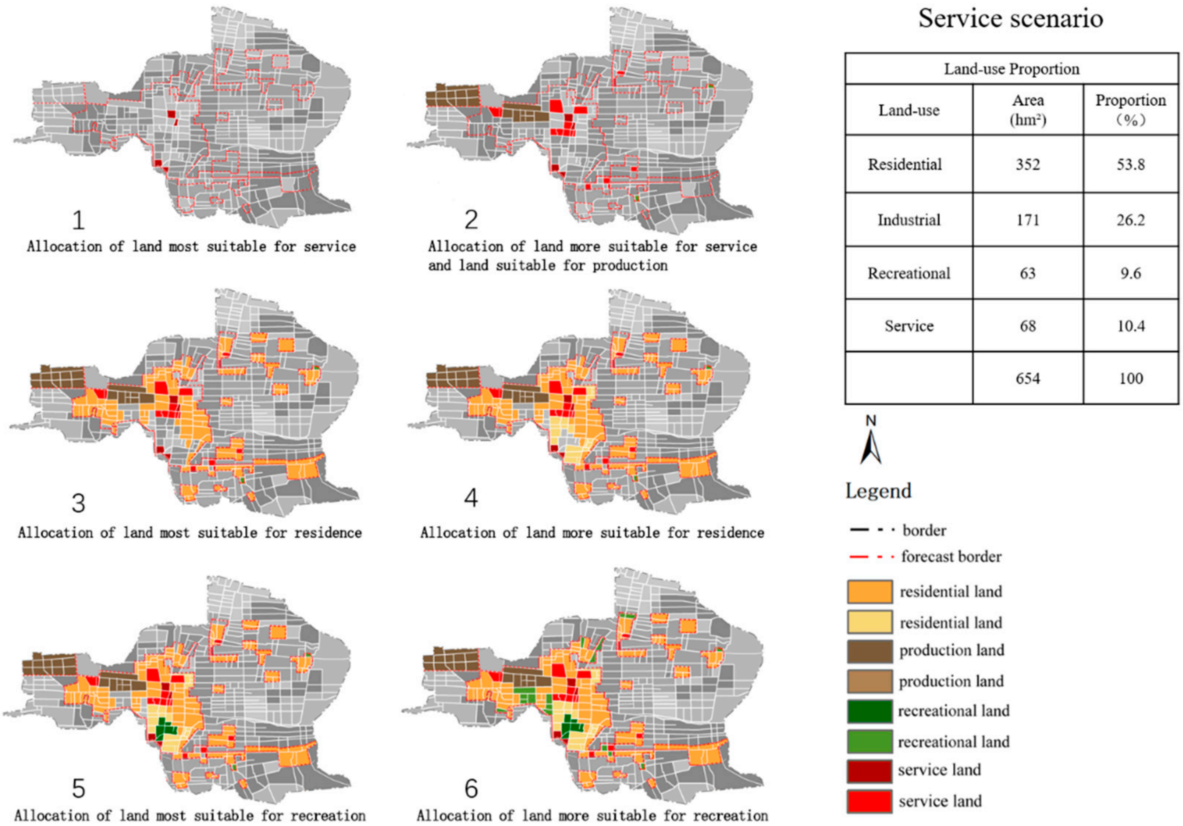
1. Regional linkage strengthening. Regional linkage strengthening disturbance refers to the policy disturbance that the regional government or central city government wants to enhance regional integration.
2. Regional linkage weakening. Regional linkage weakening disturbance refers to the policy disturbance that small towns want to develop independently from the regional economic system or production chain.
3. Smart growth. Smart growth disturbance refers to the policy disturbance that the growth of land use in small towns is subject to more stringent policy restrictions, and the quantity of land that can be developed is reduced.
4. Rapid growth. Rapid growth disturbance refers to policy disturbance in that the policy restrictions on land use in small towns are loose, and small cities acquire a large amount of developable land.

4.6.5. Model Export

According to the data from Diaozhen and the model calculation rules, the final weight of each scenario is as follows:

- Basic social scenario: 79.85%; population rejuvenation scenario: 20%; population aging scenario: 0.15%;
- Industrial scenario: 80%; service scenario: 20%;
- Basic environmental scenario: 36%; air pollution aggravation scenario: 64%; water pollution aggravation scenario: 0%;
- Regional linkage strengthening scenario: 100%.

Based on the demographic data, economic data, environmental data, and planning documents of Diaozhen, the output results of the final model are shown in the Figure 10 below:



Land-use Proportion		
Land-use	Area (hm²)	Proportion (%)
Residential	352	53.8
Industrial	171	26.2
Recreational	63	9.6
Service	68	10.4
	654	100

Figure 10. Final model output of Diaozhen.

4.6.6. Evaluation

According to the population forecast, the population of the target small town in 2029 will be about 172,000. According to the standard for residential land, the total residential land area demand is 3,440,000 square meters. In 2029, the population of the target small town is about 172,000, and the working population is about 73,000, of which the agricultural population of the target small town in 2029 is 30%, so the total demand for industrial employment is 51,100. According to the employment multiplier theory and population/job density research, the total industrial production land area demand is 213 hectares. Thus, the model export can pass the test.

5. Discussion

Quantitative analysis of cities based on open data has become a trend for future development. However, the academic community's different and relatively independent research perspectives do not allow for a practical interface between planning and implementation and the integration of resources between urban systems [47]. The 'Interactive Cities' project analyzes the current situation of small towns and better assists Pingyin County in Shandong Province, China, in building a framework for planning decisions [48]. The 'Interactive City' project proposed in this paper better assists and guides decision-making in small towns. The project evaluates and judges the reasonableness of decisions through a fine-grained analysis of sites and scenario simulations. When uncertainty occurs, it can make active and passive responses and systematically generate land use function configuration schemes to improve the resilience of decision-making. The model integrates existing technologies, such as GIS and city modeling, to try to solve the problem of uncertainty in urban planning. At the same time, this modular and stepped urban planning modeling system helps improve planning process flexibility and adaptability. In addition, the model's application of scenario planning theory and system dynamics has promoted these theories' application and development in decision support systems and planning. In modeling and predicting the growth of small industrial-type towns in China, this interactive approach based on scenario planning theory serves as a decision support. It promotes sustainable development [49]. The city of Tampa, Florida, further integrates urban growth prediction models with future flood risk models. It proposes a new methodology to improve scenario planning to cope with climate extremes such as sea level rise [50]. Moreover, using GIS technology to integrate and analyze spatial data can also drive innovation in GIS.

However, the current study still has some limitations. Subjectivity in the project cannot be eliminated, and the subjective preferences of decision-makers still influence weighting decisions at each stage of the model. The short-term economic interests and personal preferences of the policymakers may affect the implementation of long-term planning, leading to limitations in the model's validity and the accuracy of the predictions. Moreover, while system dynamics theory provides tools to simulate the dynamic behavior of a system and helps to identify critical feedback loops in the system, the impact of these models on future-oriented planning remains limited. While most land-use models are designed to predict future development states, their role in supporting planners in formulating forward-looking strategies is still limited by the current level of knowledge [51]. In addition, the processual and mechanical nature of modeling has resulted in a solidification of thinking. Incorporating innovative ideas into models remains a challenge. Therefore, future research needs to pay more attention to how to break through these limitations and enhance the flexibility and foresight of models to better support decision-makers in facing complex and dynamic urban development challenges.

6. Conclusions

The city is a complex system that is always in the process of change. The traditional planning mode inevitably has the characteristics of subjectivity and hysteresis. Correctly understanding the uncertainty in urban development and controlling the impact of uncertainty with as little cost as possible is an important issue to be urgently solved in urban planning. Meanwhile, modern urban planning requires a planning and management approach that involves all stakeholders. As a laboratory of urban planning theory, the urban model has the potential to become a platform for urban decision-making participants to negotiate together.

In addressing these issues, the 'Urban Interaction' project aims to develop an integrated urban modeling system applying a modular and stepwise system based on simple rules, allowing planners and other participants to model and visualize their scenarios. This interactive modeling system makes the planning process more transparent and allows more stakeholders to participate in decision-making. The modeling system in this paper proposes an effective planning management method that further integrates planning, planning implementation, and planning management. Compared with the traditional time-based planning mode, this method can effectively help small towns cope with various types of uncertainty, improve the efficiency of planning decision-making, and reduce the cost of trial and error. Finally, this paper hopes that this modeling system can assist the land-use decision-making of small towns in China and promote the sustainable development of cities.

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