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Scenario Simulation of the Impact of China's Free-Trade Zone Construction on Regional Sustainable Development: A Case Study of the Pearl River Delta Urban Agglomeration

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Abstract: Regional sustainable development is a complex process driven by multiple factors, such as the economy, society, and environment. China has made a series of major adjustments and devised plans, including the establishment of a pilot free-trade zone, to promote regional sustainable development. The pilot free-trade zone, characterized by free trade and the opening up of institutions, changes the path and mode of regional sustainable development to a certain extent. However, an effective empirical quantitative analysis to verify the impact of the pilot free-trade zone on regional sustainable development is lacking. This paper employs the system dynamics method to predict the social–economic–environmental development trends and key control factors of the Pearl River Delta urban agglomeration by considering the unique advantages of system dynamics. The construction of a pilot free-trade zone was set as a control variable to analyze its promoting effect on regional sustainable development. Next, the most suitable model for sustainable development for the future was determined. The results indicate that the construction of the pilot free-trade zone led to significant growth in indicators such as import and export trade, total economic volume, income, and labor force, all of which are conducive to regional sustainable development. Practically, the simulation results provide decision support for promoting the sustainable development of the Pearl River Delta urban agglomeration.

Keywords: regional sustainable development; pilot free-trade zone; system dynamics; simulation; decision support

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Citation: Liu, X.; Wang, Z.; Cui, X. Scenario Simulation of the Impact of China's Free-Trade Zone Construction on Regional Sustainable Development: A Case Study of the Pearl River Delta Urban Agglomeration. *Sustainability* **2021**, *13*, 8083. https://doi.org/10.3390/su13148083

Academic Editor: Bruce Morley

Received: 9 June 2021
Accepted: 17 July 2021
Published: 20 July 2021

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1. Introduction

The concept of sustainable development is recognized worldwide. It is used to promote intergenerational justice by emphasizing the interactive relationships between human and natural systems. On the one hand, in terms of the sustainable development of economic and social systems, different countries and regions need sustainable economic growth patterns to avoid falling into slow or even negative growth. At the same time, the problem of labor income inequality and the huge burden placed by a growing population on education and health resources must be avoided [1,2]. On the other hand, there are several complex nonlinear feedback mechanisms among economic, social, and natural systems. The status of these feedback loops directly indicates the sustainability of regional development [3,4]. Uncoordinated interactions may trigger a cascade effect and affect global and regional sustainable development [5–7]. In the present Anthropocene era, the impact of human activities on the global atmosphere, planetary hydrology, and ecosystems has never been greater, and the original feedback mechanisms between human and natural systems are significantly disrupted [8–10]. Excessive use of natural resources and environmental disturbance has severely challenged sustainable development worldwide. In

summary, sustainable development can be understood primarily as the coordinated and orderly development of economic, social, and natural systems involving key indicators, such as the scale and pattern of economic development, labor force income levels, medical and educational resource supply, and environmental quality.

China has achieved rapid economic and social development since its reform and opening up; however, it still faces problems such as environmental pollution and income inequality. China has made significant adjustments in certain regions, including the establishment of free-trade zones, to promote sustainable development of the regional economy. Deardorff proposed that (1) a free-trade zone refers to an area where import duties are exempt and storage and processing are provided for imported goods and (2) a foreign trade zone can also be termed as a free zone, free-trade port, or bonded warehouse [11]. The free-trade zones are important platforms for China to practice high-quality development, which involves political, economic, social, cultural, and ecological aspects. In this sense, the establishment of China's free-trade zones promotes regional sustainable development. That is, it improves economic openness and development and facilitates trade and investment and personnel exchange. As China's pilot free-trade zones are aimed at promoting institutional innovation and facilitating free trade, the impact of the construction of a free-trade trial zone on regional sustainable development can be analyzed from the interaction between free trade and sustainable development.

In this study, a system dynamics model that reflects the relationship between free-trade zones and regional sustainable development was constructed. The contributions of this study primarily include two aspects. On the one hand, most studies involve the impact of free-trade zone construction on economic and social factors, such as trade development, economic growth, and human mobility, and few studies consider the compound impact including environmental factors. On the other hand, qualitative models have often been employed to analyze the effects of pilot free-trade zones on regional sustainable development as compared with quantitative models. Therefore, this study analyzes the compound impact of free-trade zone construction on the economy, society, and environment with quantitative research as a complement to previous studies. Additionally, most quantitative models used were econometric models, and the complex feedback relationships between variables were rarely considered. A system dynamics model can reflect the complex relationship between elements—which is conducive to simulating complex processes—and thus provides an effective quantitative approach to assess the effect of pilot free-trade zones on sustainable development [12]. Therefore, we present the compound economic, social, and environmental impacts of free-trade zone construction through the feedback relationships between different elements in the system dynamics model. On this basis, the authenticity of the model was verified, and the Pearl River Delta urban agglomeration was chosen to verify the impact of building or not building a pilot free-trade zone on the key indicators of regional sustainable development. The simulation results of the system dynamics model demonstrate how to devise policies concerning regional sustainable development in the context of building pilot free-trade zones.

This article is organized as follows: Chapter 2 reviews the literature; in Chapter 3, a system dynamics model, which embeds the construction of the pilot free-trade zone into the regional social–economic–environmental system as a variable, is constructed. Chapter 4 presents the empirical simulation results; and Chapter 5 summarizes the study and provides suggestions for policymakers.

2. Literature Review

As aforementioned, China is constructing pilot free-trade zones to facilitate institutional innovation and promote free trade. Free trade can directly influence economic growth and transportation generation as well as population movement, and it may also transfer environmental pollution or improve the environment. Therefore, we assume that the construction of free-trade zones not only promotes the development of free trade as

a way to promote economic and social development but also has uncertain effects on the environment.

In this regard, this paper analyzes the impact of pilot free-trade zones on regional sustainable development by summarizing the key relationships among free trade and society, economy, and environment. Admittedly, the economic and social boosting effects of free trade are significant; however, there is a need for further deepening at the theoretical level, including the key questions: What are the global universal and regional differential impacts of free trade? How does free trade contribute to population agglomeration? Furthermore, in the context of sustainable development, its positive or negative impact on environmental factors and methods available to effectively quantify it must be discussed. Thus, the theoretical logic of free trade on sustainable development can be clarified to support the subsequent quantitative analysis.

Notably, promoting free trade for economic growth has been extensively debated in academia. In theory, the economic value of free trade can be analyzed from the perspective of effective allocation of global resources, particularly with regard to regional comparative advantages. According to the theory of regional comparative advantage, each region has different comparative advantages and should use them to rationally allocate resources and achieve sustainable development through complementary advantages [13]. The focus of the industrial development and service targets of different free-trade zones differs to a certain extent because of factors such as geography, resource endowment, and policies [14].

The development of free trade also drives the rapid and free exchange of human capital, which is an important resource for national economic development as well as an endogenous element for social and economic development. The classical political economy emphasized the role of material capital. Although Marx's theory of labor value can be regarded as a manifestation of human capital, no clear definition of human capital exists [15]. With the advancement of science and technology and the development of social productivity, research on human capital theory peaked during the 1950s and 1960s. Theodore W. Schultz and Gary S. Becker—two prominent economists from the United States—analyzed the role of human capital investment in promoting social and economic development from the macro and micro perspectives, respectively [16,17]. Edward applied quantitative analysis to explore the role of human capital elements in social and economic development, demonstrating that high-tech talent is a powerful driver of economic growth and development [18]. After the 1980s, a "new economic growth theory" based on the "knowledge economy" began to crystallize, thereby further illustrating the effect of endogenous variables, such as human capital and education level, on economic growth that employs mathematical methods [19,20].

With the rapid development of world economic integration brought about by the liberalization of global trade, most countries—especially developing countries—have increasingly focused on ecological and environmental issues. Currently, the impact of free trade on the environment is extensively debated in academia. Some scholars posit that free trade may negatively affect the environment and that the improvement in trade openness may exacerbate issues related to environmental pollution in developing countries; other scholars suggest that trade liberalization may have a positive effect in the long run because it will help reduce environmental pollution.

Grossman and Krueger studied the effects of the North American Free Trade Agreement on the environment by using panel data from 42 countries to analyze the relationship between ambient air quality and trade development and found an inverted U-shaped relationship between the two [21]. Jalil and Mahmud investigated the impact of trade liberalization on China's per capita CO_2 emissions from 1975 to 2005 based on the environmental Kuznets curve model and concluded that free trade reduces environmental pollution [22]. Baghdadi et al. analyzed and found a negative relationship between free trade and ambient air quality by using panel data of 182 countries from 1980 to 2008 [23]. Zameer et al. found a two-way relationship in the long run between trade openness and

energy use by analyzing the cointegration relationship among indicators such as FDI, trade openness, energy use, and economic growth in India from 1985 to 2017 [24].

The literature analysis reveals that free trade significantly impacts the promotion of the economy, society, and environment. First, free trade can realize the systematic allocation of global resources; however, variability will be present in different regions, and its impact must be analyzed in the context of the actual development of these regions. Second, free trade can promote the rapid and free flow of human resources, which further affects technological progress and economic growth. Third, free trade may have adverse effects on environmental protection in developing countries in the short term; however, in the long run, it has a positive effect on environmental improvement. Theoretically, economic, social, and environmental issues are significantly affected because the construction of pilot free-trade zones effectively promotes free-trade development. Ultimately, constructing pilot free-trade zones may alter the process and mode of regional sustainable development.

Furthermore, from the perspective of research, because most studies focus on the impact of free trade on single factors, such as economic development model, human resources, and environmental pollution, it is necessary to quantify the comprehensive impact of free-trade zone construction on regional sustainable development from a composite perspective, so as to provide scientific decision-making support for the regulation of the regional sustainable development model.

3. Materials and Methods

3.1. Study Area

The Pearl River Delta urban agglomeration, one of the three most important urban agglomerations in China (the other two being the Beijing–Tianjin–Hebei and the Yangtze River Delta urban agglomeration), comprises Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Huizhou, Zhongshan, Jiangmen, and Zhaoqing. As one of the regions with the highest degree of openness and strongest economic vitality in China, the Pearl River Delta urban agglomeration is strategically important in the national development pattern.

Despite the developments, the Pearl River Delta urban agglomeration faced a series of roadblocks to its development in recent years. Particularly, the growth of its export-oriented economy has been weak, with the total imports and exports declining from RMB 1047.4 billion in 2013 to RMB 961.2 billion in 2017. The economic growth rate has slowed, with an annual GDP growth rate of 8–9% since 2014, which is lower than that from 2000 to 2014 when the annual GDP growth rate exceeded 10% every year. The environment in this urban agglomeration is deteriorating, and the comprehensive pollution index of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, and O_3 increased from 4.05 in 2015 to 4.25 in 2017. The permanent population increased from 42.9 million in 2000 to 61.51 million in 2017 because of an influx of immigrants. Although this ensured sufficient labor and the presence of highly skilled personnel in this area, basic public services, such as medical care and education, are impacted.

In 2015, China established a China (Guangdong) Pilot Free-Trade Zone in the three core cities of Guangzhou, Shenzhen, and Zhuhai to enhance the level of opening up of the Pearl River Delta urban agglomeration as well as the quality of regional sustainable development and to drive the transformation of regional development. Although the China (Guangdong) Pilot Free-Trade Zone has enhanced regional economic growth, open development, and environmental protection in recent years, the results are unsatisfactory. Thus, the role of pilot free-trade zones in facilitating regional development needs to be enhanced to further promote regional sustainable development. This article analyzes the improvement in the main sustainable development indicators of the Pearl River Delta urban agglomeration from the present to 2035, the period during which the high-quality construction of free-trade pilot zones is being further promoted.

3.2. Model and Feedback Structure

The system dynamics model mainly integrates three levels of sustainable development, namely, the economy, society, and environment. It involves key subsystems, such as trade growth, technological innovation, economic and fiscal growth, population growth, public service levels, and environmental quality. With reference to the economic spillover system dynamics model of the pilot free-trade zone [25], and based on the research focus and development characteristics of the Pearl River Delta urban agglomeration, this paper includes variables, such as increase in import and export trade, level of technological innovation, permanent population, economy scale, immigration of talent and labor force, fiscal revenue, financial guarantee level of environmental regulation, traditional manufacturing scale, and per capita disposable income, in the model. Determining the boundary of the model is the basis of modeling; therefore, the system dynamics model was established within the aforementioned boundary.

The feedback between subsystems is complex. Regarding its effects, the pilot free-trade zone may significantly impact the economy, society, and environment; however, the impact differs by region and can be divided into four categories, namely, positive, negative, positive and negative, and none [26]. In terms of factors, the pilot free-trade zone influences regional sustainable development in four ways: increasing the volume of trade and investment, expanding the economic scale, promoting social well-being, and improving environmental quality [27–29]. Technological innovation is considered to play an important role in promoting regional sustainable development and is included as a variable based on the advantages of technological innovation in the Pearl River Delta urban agglomeration. Trading volume and investment, mainly characterized by imports and exports, significantly affect economic growth. Social well-being is mainly impacted by economic growth and population inflow, which form a complex cascading effect. Regarding environmental quality, the Ambient Air Quality Index released by the Department of Ecology and Environment of Guangdong Province was adopted. The index considers the following pollutants: SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, and O_3. The larger the index, the higher the degree of comprehensive pollution (Figure 1).

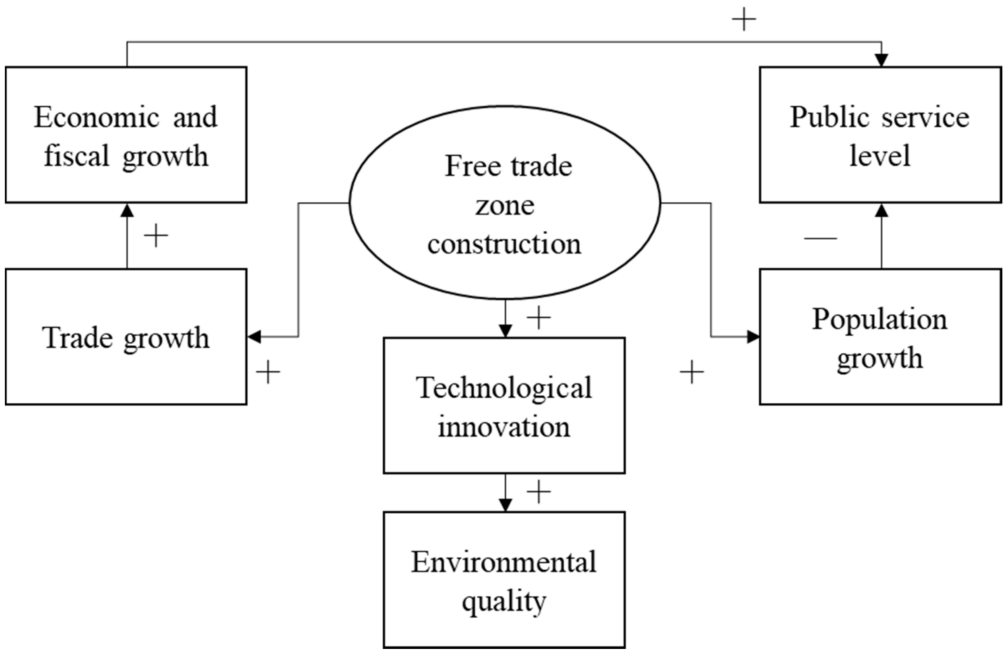


Figure 1. Basic structure of the system dynamics model.

In this specific model, feedback comprises the following: (1) construction of the pilot free-trade zone has a positive cascading effect on import and export, economic scale, and level of economic development; (2) promoting effect of constructing pilot free-trade zones on technological innovation and the negative cascading effect of the traditional industrial scale on environmental quality; (3) promoting effect of constructing pilot free-trade zones on the permanent population and the complex cascading effect of the construction of the pilot free-trade zones on the level of medical and educational services. The system dynamics model has the following two functions:

(1) forecasting the development trend of key economic, social, and environmental variables in the Pearl River Delta urban agglomeration; and

(2) simulating the impact of the construction of a pilot free-trade zone on the sustainable development of the Pearl River Delta urban agglomeration.

3.3. Subsystems and Variable Assignment

The model comprises key subsystems such as policy, trade economy, technological innovation, population, public services, and environmental quality (Table 1).

(1) In the policy subsystem, the construction of a pilot free-trade zone was regarded as a core variable because it may have a significant direct impact on the total import and export trade, level of technological innovation, and increase in talent and labor in the Pearl River Delta urban agglomeration.

(2) The trade economic subsystem mainly characterizes the positive effect of the construction of pilot free-trade zones on import and export trade, economic development level, fiscal revenue, and per capita disposable income.

(3) The scientific and technological innovation subsystem mainly characterizes the promoting effect of the construction of free-trade zones on technological innovation and how it further affects the proportion of traditional manufacturing.

(4) The population subsystem primarily demonstrates the role of the construction of pilot free-trade zones in attracting individuals and its influence on the trend of permanent population.

(5) The public service subsystem essentially demonstrates the impact of the construction of pilot free-trade zones on the level of public services, such as medical education and higher education, which are also affected by the interaction of population and service scale growth.

(6) The environmental quality subsystem primarily characterizes the impact of the construction of pilot free-trade zones on environmental quality, which can be used as an important variable for analyzing social well-being.

Data were mainly obtained from the statistical yearbooks of cities in China's Pearl River Delta urban agglomeration and Guangdong Province. The equation for each variable was repeatedly trained through parameter learning algorithms, and the parameters were determined (the details of equations can be seen in Appendix A). The parameters include the arithmetic average method calculated based on historical data and related standard reference values; trend estimation algorithm recursed based on data trend; table function method, wherein scenarios were controlled by establishing the Vensim table function; and linear regression method, wherein the parameters were determined using a univariate or multiple linear regression model with the support of SPSS 19.0 and the Urban Regional Planning Model System [30].

Table 1. Key variables and indicators.

Variables	Types	Indicators
Total import and export trade	Level variable	Total import and export trade converted at the average annual exchange rate of RMB to USD
Increase in import and export trade	Auxiliary variable	Monetary amount of increase in import and export trade
Growth rate of import and export trade	Auxiliary variable	Growth rate of import and export trade
Opening-up level	Auxiliary variable	Economic openness
Economic scale	Auxiliary variable	GDP
Economic development level	Auxiliary variable	GDP per capita
Fiscal revenue	Auxiliary variable	Local general public budget revenue
Proportion of fiscal revenue to GDP	Auxiliary variable	Proportion of fiscal revenue to GDP
Per capita disposable income	Auxiliary variable	Per capita disposable income of permanent residents
Technological innovation level	Auxiliary variable	Proportion of R&D expenditure in GDP
Traditional manufacturing scale	Auxiliary variable	Significantly related to the added value of the secondary industry
Proportion of traditional manufacturing industry	Auxiliary variable	Proportion of traditional manufacturing industry
Resident population	Level variable	Resident population
Increase in permanent population	Auxiliary variable	Amount of increase in import and export trade
Growth rate of permanent population	Auxiliary variable	Growth rate of permanent population
Medical service scale	Auxiliary variable	Health workers
Medical service level	Auxiliary variable	Number of health workers per 10,000 people
Higher-education scale	Auxiliary variable	Number of students in regular colleges and universities
Higher-education level	Auxiliary variable	Number of students in regular colleges and universities per 10,000 people
Financial security level of environmental regulation	Auxiliary variable	Significantly related to local general public budget revenue
Environmental quality level	Auxiliary variable	The Ambient Air Quality Index released by the Department of Ecology and Environment of Guangdong Province was adopted. The index considers the pollutants SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, and O_3. The larger the index, the higher the degree of comprehensive pollution.

3.4. Model Visualization

The system dynamics model was developed by decomposing the variables of the subsystems in Figure 1, and the visual expression and simulation operation were realized using the Vensim PLE platform (Figure 2). The time period was set to 2000–2035, that is, the unit is the year, Final Time = 2035 and Initial Time = 2000 in the model system.

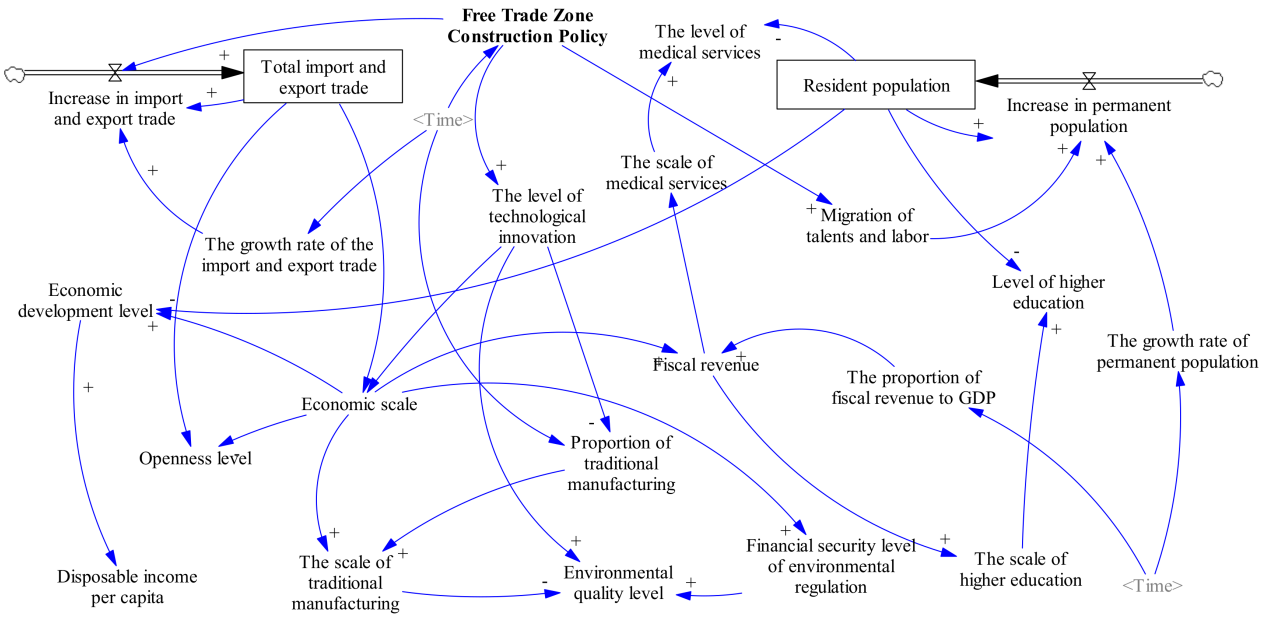


Figure 2. Dynamic model of the value simulation system for free-trade composite ports.

4. Model Experiment and Result Analysis

4.1. Verification of Model Authenticity

To verify the authenticity of the simulation results of the model, year-wise historical data from 2000 to 2014 were first fed into the Vensim PLE system for simulation operation. Next, an error comparison was conducted between the output simulated values from 2015 to 2017 and the actual values. Finally, the convergence of simulation results and authenticity of the model were ensured through repeated debugging of equation parameters [31]. As shown in Table 2, the error rate between the actual value and the simulated value from 2015 to 2017 is generally less than 5%, thus indicating that the model has been verified.

4.2. Parameter Settings in Different Scenarios in the Model

A comprehensive development scenario is key for comparing data differences between the initial state and policy scenario and measuring the impact of the construction of pilot free-trade zones on regional sustainable development. The scenarios in this model can be divided into economic growth, technological innovation, and migration of talent and labor based on the dynamic mechanism of this impact on the economy, society, and environment in the aforementioned analysis and the development practice of the Pearl River Delta urban agglomeration.

(1) Economic growth: Although empirical studies have indicated the uncertainty regarding the construction of pilot free-trade zones affecting economic growth, some research in China, as shown in Table 3, has suggested that the construction of these zones may promote trade growth by approximately 1–3.4 percentage points (Table 3), thereby promoting coordinated economic growth among regions. Given that the Pearl River Delta City cluster is one of the most developed regions in China in terms of foreign trade, an assumption based on the median principle is that the construction of pilot free-trade zones will promote the increase of import and export trade volume by 1.5 percentage points,

which is considered as economic growth. Owing to the long-term nature of the construction of pilot free-trade zones, the trade growth rate is expected to increase by 1.5 percentage points by 2035.

Table 2. Test results of the stack and flow in systems.

Year	Variable	Total Import and Export Trade (RMB 100 Million)	GDP (RMB 100 Million)	Permanent Population (10,000 People)	Local General Public Budget Revenue (RMB 100 Million)	Ambient Air Quality Index
2015	Actual value	60,755	63,382	5874	6392	4.05
	Simulated value	57,611	66,538	5879	6234	4.23
	Error rate	−5.2%	5.0%	0.1%	−2.5%	4.5%
2016	Actual value	60,436	69,070	5998	6924	3.99
	Simulated value	60,974	72,038	6002	6861	4.23
	Error rate	0.9%	4.3%	0.1%	−0.9%	6.0%
2017	Actual value	64,883	75,710	6151	7456	4.25
	Simulated value	64,348	77,680	6127	7520	4.22
	Error rate	−0.8%	2.6%	−0.4%	0.9%	−0.7%

Date resource: statistical yearbooks of cities in China's Pearl River Delta urban agglomeration and Guangdong Province.

Table 3. Conclusions on the promotion of trade growth by constructing some of China's pilot free-trade zones.

Policy Scenarios	Trade Growth Rate (Based on Low Expectations)	References
Establishing the China–Japan–Korea Free-Trade Area	3.36%	Kuang [32]
Establishing the China–India Free-Trade Area	1.02%	Yu et al. [33]
Establishing the China (Guangdong) Pilot Free-Trade Zone	1–2% (replaced by quarterly GDP growth rate)	Ying and Fan [34]

Note: The unary linear regression test demonstrates that there is a significant positive correlation between the GDP (independent variable X) of the Pearl River Delta urban agglomeration and the import and export trade volume (dependent variable Y), that is, $Y = 0.118 \times X + 2450$, $R^2 = 0.84$. Therefore, the GDP growth rate can represent the growth rate of import and export trade.

(2) Technological innovation: A quantitative basis for the relationship between pilot free-trade zones and technological innovation is lacking. Therefore, the method of setting control targets based on the current situation was adopted to formulate technological innovation scenarios for the construction of pilot free-trade zones. The investment in R&D expenditure was calculated based on the proportion of R&D expenditure of the entire society in GDP. The results demonstrate that the average investment in R&D expenditure was 2.9% for the Pearl River Delta urban agglomeration, 4.3% for Shenzhen (the highest), and between 1% and 2.5% for other cities. According to the goals proposed by the Outline Development Plan for the Guangdong–Hong Kong–Macao Greater Bay Area, the Pearl River Delta urban agglomeration will build an open regional collaborative innovation community, requiring the free and orderly exchange of innovation resources among cities. With this as the long-term control goal, the construction of a pilot free-trade zone is expected to narrow the technological innovation gap between Shenzhen and other cities in the urban agglomeration. The average R&D investment for the Pearl River Delta urban agglomeration is estimated to reach 3.5%, an overall increase of approximately 0.6% from the current stage to 2035, considering the international experience of post-industrialized countries whose R&D investment has reached 2.5–3%.

(3) Talent and labor migration: The construction of a pilot free-trade zone may facilitate a large influx of talent and labor, thus expanding the size of the region's permanent

population. Thus, the carrying capacity of medical care and higher education in the region will experience further challenges, which should be matched with economic development and public service construction. The scenario of talent and labor migration explores the changing trend of public services and social security levels in the Pearl River Delta urban agglomeration under the interactive influence of population and economic growth. The population is expected to increase by 0.5% from the current stage to 2035, considering the scenarios of other urban agglomerations in China [31].

A policy scenario table was generated (Table 4) based on the aforementioned hypothesis.

Table 4. Policy scenarios for the construction of pilot free-trade zones.

Scenarios	Policy Scenario		No-Policy Scenario	
	Expectation of the Policy Impact	**Parameter Control**	**Expectation of the Policy Impact**	**Parameter Control**
Economic growth	Growth of import and export trade	Increasing by 1.5 percentage points by 2035	Original state	Maintaining historical trends
Technological innovation	Growth in R&D expenditures	3.5%	Original state	2.9%
Immigration of talent and labor	Increase in permanent population	Increasing by half a percentage point by 2035	Original state	Maintaining historical trends

4.3. Scenario Simulation and Analysis

The impact of the construction of pilot free-trade zones on the sustainable development of the Pearl River Delta urban agglomeration was determined by comparing the scenarios wherein pilot free-trade zone are constructed and those wherein they are not constructed and discussing the development trends as well as differences in the key indicators of regional sustainable development.

(1) Analysis of the economic impact: In Figure 3, the modeling and adjustment of parameters demonstrate that the construction of a pilot free-trade zone has a cumulative effect on certain variables, such as import and export trade and economic scale. Based on the current development trend, the total import and export trade of the Pearl River Delta urban agglomeration is expected to amount to RMB 11,164.2 billion by 2035, an average annual increase of 3.4% from RMB 6488.3 billion in 2017; moreover, the construction of the pilot free-trade zone will bring about an additional increase of RMB 1.5456 billion. The total production value of the Pearl River Delta urban agglomeration is predicted to reach RMB 18,077.9 billion by 2035, an average annual increase of 5% (calculated at current prices) from RMB 7571 billion in 2017, with the construction of the pilot free-trade zone bringing in about an additional increase of RMB 50,482 billion. The scale of trade has not only expanded, but the endogenous economic growth has also been promoted through technological innovation. This observation is attributed to the free-trade zone construction increasing the size of the economy by enhancing the scale of foreign trade, and therefore, growing the GDP significantly. Furthermore, the free-trade zone construction can stimulate the endogenous power of economic development by promoting scientific and technological innovation, thereby guaranteeing that the economic development momentum of the Pearl River Delta urban agglomeration no longer relies excessively on foreign trade. This has led to a steady decline in the level of opening up, which ultimately stabilized at 57% and reduced the risks related to economic dependence on foreign countries to a certain extent. In this regard, the construction of a pilot trade zone and the degree of dependence on foreign trade do not always promote each other and can inhibit each other [35]. However, this does not mean that the pilot free-trade zone may lead to a decline in the level of economic openness and development. This issue should be considered from the perspectives of promoting endogenous growth and high-quality outward development.

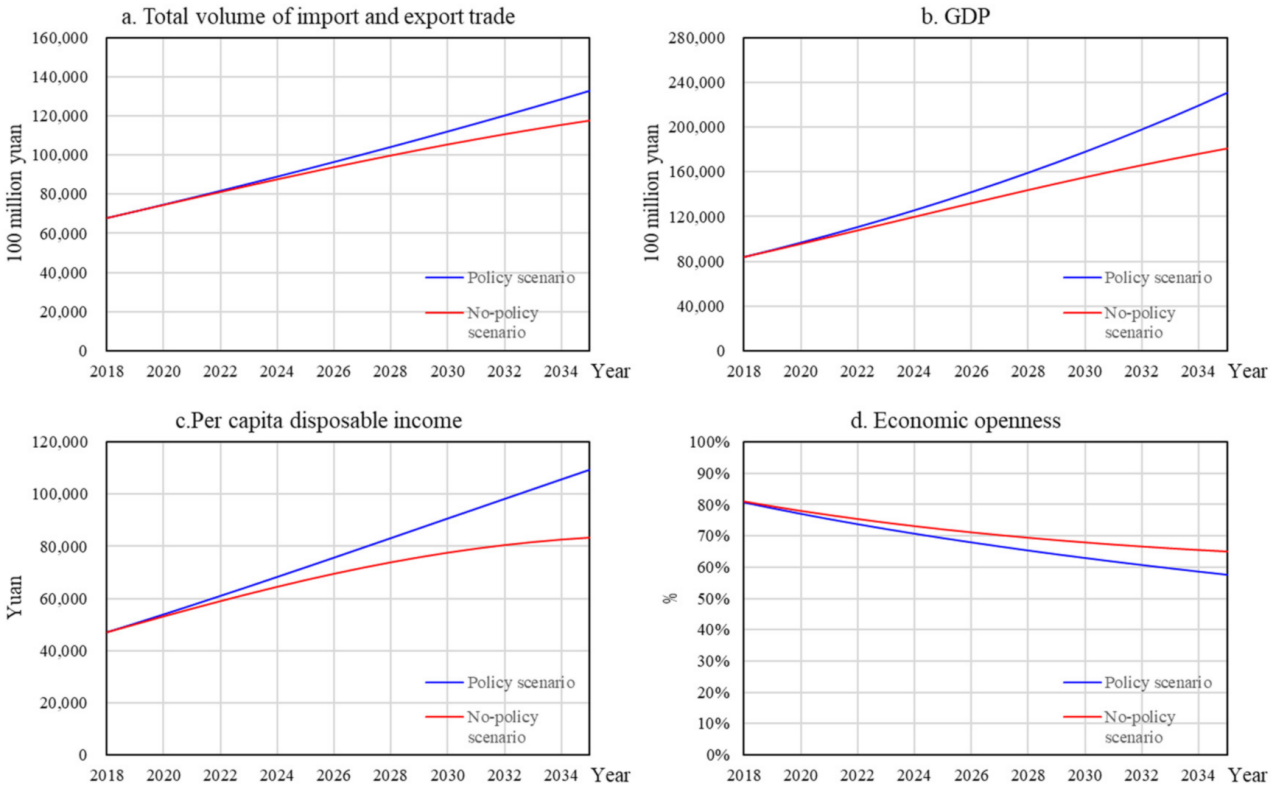


Figure 3. Simulation results of economic indicators.

Therefore, the stability of a regional economic system must not rely excessively on foreign trade but should also focus on the endogeneity of economic development and the driving ability of science and technology innovation. In summary, the free-trade zone construction can not only promote the expansion of the economic scale of the Pearl River Delta urban agglomeration but also facilitate the adjustment of its economic development model.

(2) Analysis of social and environmental impact: The simulation results of the system dynamics (Figure 4) demonstrate that the construction of pilot free-trade zones promotes the inflow of external talent and labor and simultaneously enhances the level of medical care and higher education through economic development. The statistics released by Guangdong demonstrate that the permanent population in the Pearl River Delta urban agglomeration increased 2% per year from 2000 to 2017, with a growth rate of 2.45% in 2018 (Statistics of Guangdong Population Development Analysis in 2018). This indicates that the Pearl River Delta urban agglomeration is more suited to drawing in talent. Based on the current population trends, the permanent population in the Pearl River Delta urban agglomeration is expected to reach 88.22 million by 2035, an average annual increase of 2% from 61.51 million in 2017. This area's population is predicted to reach a larger size, and the construction of pilot free-trade zones will stimulate the influx of additional external talent and labor, thereby strengthening the agglomeration effect. The permanent population is expected to amount to 91.97 million by 2035, which is 3.75 million more than the population in case the pilot free-trade zones are not constructed. The number of health workers and of students in colleges and universities per 10,000 people will reach 133 and 385, respectively. This observation is attributed to the free-trade zone construction not only promoting the agglomeration of more talent and labor in the Pearl River Delta urban agglomeration but also contributing to higher fiscal revenues through economic growth. Accordingly, higher fiscal revenues guarantee that the Pearl River Delta urban agglomeration can provide more medical and educational resources to the growing population in the future. The construction of pilot free-trade zones also positively impacts environmental quality control by improving the synergies between technology and innovation, reducing the proportion

of traditional manufacturing, and increasing investment in environmental protection. This ultimately promotes high-quality green economic development. The comprehensive environmental air quality index is expected to decrease to 3.83 by 2035, which is 1.26 lower than that if pilot free-trade zones are not constructed, thus indicating that the concentration of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3, and other major pollutants will further decline.

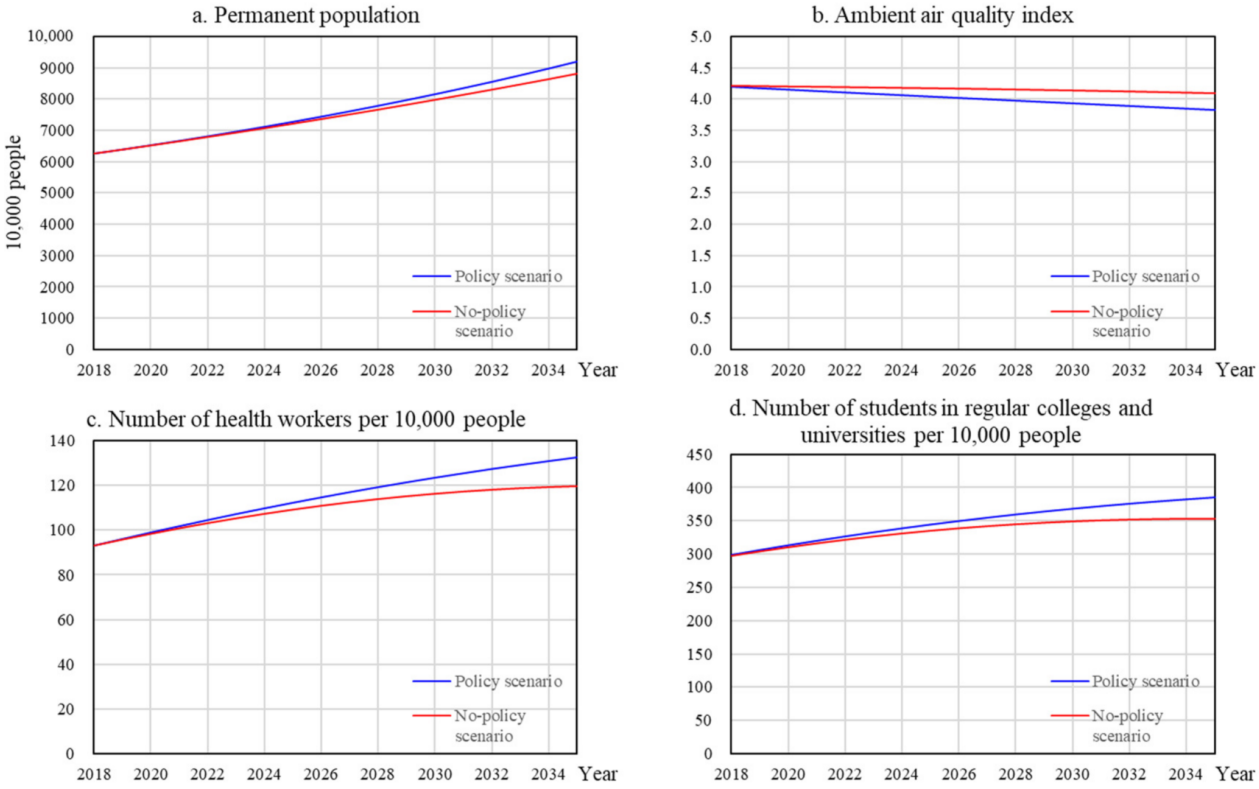


Figure 4. Simulation results of social and environmental indicators.

Overall, on the one hand, the free-trade zone construction in the Pearl River Delta urban agglomeration will effectively gather more talent and labor force and provide more medical and educational resources by improving fiscal revenue, thereby enhancing the level of sustainable social development. On the other hand, the free-trade zone construction will improve the environmental level because it effectively enhances the green level of economic development by improving the level of science and technology innovation and reducing the proportion of manufacturing industries.

5. Conclusions and Policy Implications

5.1. Conclusions and Discussion

The simulation results of the system dynamics model demonstrate that the construction of pilot free-trade zones promotes the sustainable development of the Pearl River Delta urban agglomeration, mainly reflected in the aspects of the economy, society, and environment.

In terms of economic impact, the construction of pilot free-trade zones substantially promotes the level of import and export trade and expands the trade scale and economic scale on the original basis. In this process, the endogenous driving force of economic growth continues to be strengthened with the advancement of technological innovation. Consequently, the level of the external economy gradually declines and stabilizes at a certain level, thereby reducing risks related to dependence on the external economy to a certain extent. This also implies that the construction of pilot free-trade zones and dependence on regional foreign trade do not always promote each other and may restrain each other during the development process.

In terms of social impact, the construction of pilot free-trade zones substantially promotes an increase in labor and external talent, thus enhancing economic development and promoting continuous improvement in the level of medical care and higher education in the region. Furthermore, the construction of pilot free-trade zones affects the government's regulation of environmental quality, which is primarily realized through the transformation of the industrial structure brought about by technological innovation. In this process, the proportion of the output value of the traditional manufacturing industry in total output value continues to decline, and the proportion of the output value of high-tech industries increases. The financial investment in environmental protection is also increasing, thereby making high-quality and green economic development possible. Evidently, the positive effects of free-trade zones construction on society and environment are primarily indirect, thereby reflecting the positive externalities of free-trade zones construction. That is, if social and environmental objectives are considered the initial goals of free-trade zones construction, better sustainable development effects will be obtained.

Furthermore, the sensitivity of the research method in this paper must be discussed and the limitations of the study must be summarized. On the one hand, the key parameters in the system dynamics model are selected for sensitivity analysis, and the adjustment of the parameters is found to have an uneven impact on the dynamic behavior of different system variables. In terms of specific methodology, three scenario variables, namely, economic growth, technological innovation, and immigration of talent and labor, are selected as moderation parameters to analyze the sensitivity of the primary variables. The results show that per capita disposable income and GDP have the highest sensitivity, thereby indicating that the free-trade zone construction can significantly affect the level of economic development. The total volume of import and export trade, economic openness, level of higher education, and level of medical services are the second most sensitive, thereby indicating that the free-trade zone construction can also have a positive impact on outward economic and medical education services. The sensitivity of environmental quality and permanent population is relatively low, thereby indicating that although the free-trade zone construction has a positive impact on the environment and on population attraction, the effect must be strengthened.

On the other hand, the connotations of economic and social development and environmental quality defined in the study are relatively limited, primarily macro-indicators, such as the scale and pattern of economic development, labor force income level, medical and educational resource supply, and environmental quality level, without considering micro-indicators, such as urban construction, leading to congestion and pollution.

5.2. Policy Implications

A comparison of the two scenarios wherein pilot free-trade zones are built and wherein they are not built provided valuable policy implications for promoting regional sustainable development in the context of the construction of pilot free-trade zones. First, the degree of economic openness should be enhanced to promote the coordinated development of regional economies. The construction of a pilot free-trade zone leads to significant growth in import and export trade and eliminates the trade barriers between regions, thus promoting the coordinated development of regional economies.

Second, scientific and technological innovation networks should be constructed, and the openness degree of science and technology should be enhanced. The promotion of free exchange of scientific and technological innovation not only fosters endogenous drivers of economic growth but also leads to high-quality development of areas with weak scientific research, thus making regional green and sustainable development possible.

Third, the migration of external talent and labor should be guided in a reasonable and orderly manner. Although the influx of new population ensures sufficient talent and labor, it increases the burden on the carrying capacity of public services, such as healthcare and education. A population migration mechanism should be implemented to ensure that the

demand for talent and labor in the region is effectively addressed and that basic public service resources fulfill the demands of a large section of talent and labor.

Fourth, funding channels should be expanded, and international high-level medical education and higher-education institutions should be established. The feedback structure of the system dynamics model demonstrates that adequate financial security is the key in maintaining high-level medical education and higher education. In the future, fiscal funds should be used to promote the development of education and medical care, and the opportunities brought about by the development of pilot free-trade zones should be leveraged to expand the level of regional, social development through multiple funding channels.

Author Contributions: Conceptualization, X.L. and X.C.; methodology, X.C.; software, X.L.; validation, X.L., Z.W. and X.C.; formal analysis, X.L.; investigation, X.C.; resources, Z.W.; data curation, X.L.; writing—original draft preparation, X.C.; writing—review and editing, X.L.; visualization, X.C.; supervision, Z.W.; project administration, Z.W.; funding acquisition, X.C. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by the China Postdoctoral Science Foundation, grant number "2020M672777".

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Institute of Geographic Sciences and Natural Resources Research, CAS.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of Institute of Geographic Sciences and Natural Resources Research, CAS.

Acknowledgments: The authors would like to thank H.L. (working in Institute of Geographic Sciences and Natural Resources Research, CAS) for his great support in writing revision.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Pilot free-trade zone construction = With lookup (Time, ([(0,0)—(2035,10)], (2000,1), (2017,1), (2035,1)))
Total import and export trade = INTEG (increase in import and export trade, 13,173)
Increase in import and export trade = Total import and export trade × (pilot free-trade zone construction − 1) + total import and export trade × growth rate of import and export trade
Growth rate of import and export trade = −0.05 × LN (Time—1999) + 0.197
Opening-up level = Total import and export trade/economic scale
Economic scale = (0.0144 total import and export trade ^ 1.4) ^ (LN (scientific and technological innovation level + 0.971) + 1)
Economic development level = 10,000 × economic scale/resident population
Fiscal revenue = Proportion of fiscal revenue to GDP × economic scale
Proportion of fiscal revenue to GDP = 3.139 × LN (Time)—23.789
Per capita disposable income = 0.00635 × economic development level ^ 1.34
Technological innovation level = With lookup (pilot free-trade zone construction, ([(0,0)—(10,10)], (1,0.029), (1.015,0.035)))
Traditional manufacturing scale = Economic scale × proportion of traditional manufacturing
Proportion of traditional manufacturing industry = 0.029 × (−6.515 × LN (Time) + 50)/technological innovation level
Migration of talent and labor = With lookup (pilot free-trade zone construction, ([(0,0)—(10,10)], (1,0), (1.015,0.005)))
Resident population = INTEG (increase in permanent population, 4290)
Increase in permanent population = Permanent population × migration of talent and labor force + permanent population × growth rate of permanent population

Growth rate of permanent population = −0.084 × LN (Time) + 0.66
Medical service scale = 0.285 × Fiscal income ^ 0.59
Medical service level = 10,000 × medical service scale/resident population
Higher-education scale = 1.88 × Fiscal revenue ^ 0.51
Higher-education level = 10,000 × higher-education scale/permanent population
Financial security level of environmental regulation = 0.1037 × economic scale −627.41
Environmental quality level = 1.6 × LN (traditional manufacturing scale) − 1.39 × LN (financial security level of environmental regulation) − 1.31 × technological innovation level

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