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Conceptualization and Development of a DFuzzy Model for Low-Carbon Ecocities

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Abstract: The Industrial Revolution has enabled mechanization to lead the manufacturing industry into a new era of explosive economic growth. Mass production through the use of machines has improved the overall societal prosperity in industrialized countries. The great and continuous demand of mechanization, economic growth, and energy consumption has resulted in the excessive use of natural resources and the mining of natural energy deposits. Challenges such as serious environmental pollution, ecological damage, and climate change have been identified as some of the critical issues for sustainable development. Therefore, this paper proposes a Delphi and Fuzzy (DFuzzy) model in order to institute low-carbon ecocities. DFuzzy is a scientific decision-making model with quantitative multiple attributes and artificial intelligence. Twelve specialists from the Delphi experts were interviewed, including chief executive officers (CEOs) of industries, management committee members, and senior academics, all of whom have 15 years of experience in urban planning practice. After a three-round Delphi process with 17 criteria that were taken from the literature, four criteria of the DFuzzy model were recognized by experts: policy norms, resident cooperation, pollution prevention and control, and ecological reserves. The practical application of the DFuzzy model took three areas as examples: the Baiyun District and Conghua District of Guangzhou City, and the Dahu Community of Kaohsiung City. Through the experts' consensus in the two-round Delphi process, the four criteria, as the input basis, demonstrated the objective quantitative calculation function of the DFuzzy model and also indicated that the model established in this study provides a reference for evaluating low-carbon ecocities.

Keywords: industrial revolution; environmental pollution; climate change; Delphi method; fuzzy logic theory; artificial intelligence; decision support; sustainable development

1. Introduction

The global environment has become heavily polluted, leading to the greenhouse effect, climate anomalies, and changes, which have gradually jeopardized human life and property as well as biodiversity. [1]. However, estimates by the Intergovernmental Panel on Climate Change (IPCC-A UN agency) indicated that the average global temperature in 2019 would be 1 °C higher than the average global temperature before the Industrial Revolution [2]. Figure 1 presents global mean estimates based on land and ocean data [3]. The IPCC 2018 Special Report on global warming of 1.5 °C clearly describes that, compared with 1750, global warming caused by and following the Industrial Revolution has increased the global temperature by approximately 1.5 °C. This temperature change has increased climate-related risks to human health, living conditions, security, food security, water supply, and economic growth. These risks will increase further with a temperature increase of 2 °C.

A temperature increase of 1.5 °C would cause a water resource crisis and water shortages, affecting more than 100 million people globally. If global warming increases the temperature by 2 °C, the water resource crisis would affect more than 200 million people globally [2].

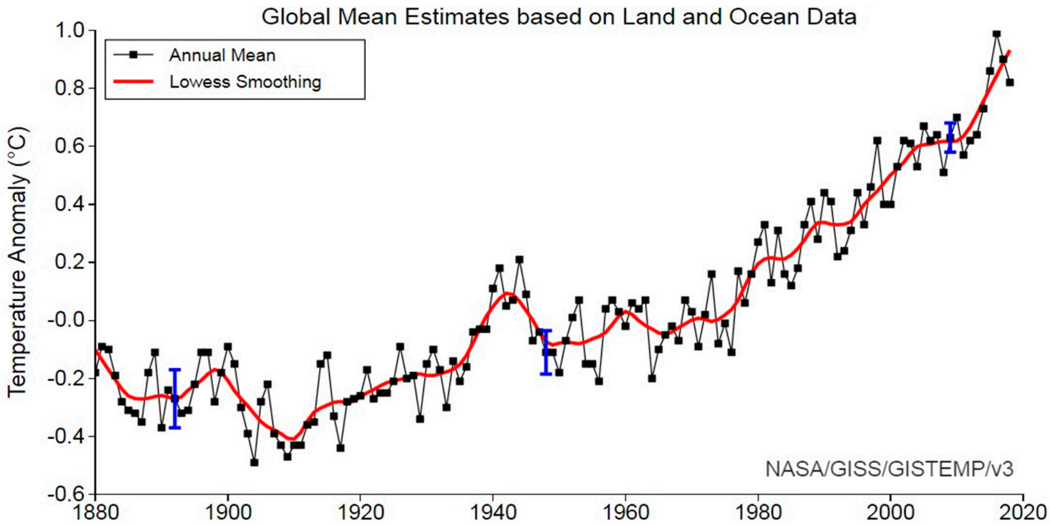

Figure 1. Global mean estimates based on land and ocean data (NASA 2019) [3].

To effectively keep the global temperature increase under 1.5 °C, the IPCC has also proposed that a rapid and long-term transition of energy use must be undertaken due to problems related to energy, land, urban infrastructure (including transportation and architecture), and industrial systems. For example, the use of low-carbon vehicles is expected to reach 35–65% by 2050, and the electricity share of energy demand in buildings should reach 55–75%. Additionally, CO_2 emissions from the industrial sector are expected to be reduced by 75% to 90% in 2050 compared with 2010. Holding the global temperature rise to under 1.5 °C can only be achieved if the three aforementioned conditions are met. To cope with issues of global climate and environmental change, the ecocity concept has become an ideal goal in urban development in recent years [4]. Additionally, urban development-oriented ideas such as promoting alternative fuel vehicles, using solar energy equipment in residential situations, cultivating low-carbon living habits [5], providing environmental education [6,7], constructing green buildings [8,9], and implementing green community construction have been developed with the aim pf achieving the ideal goal of a low-carbon city [10,11].

In the ever-changing and ever-improving field of technology and rapid economic development, explosive growth has been observed in various industries. For example, factors such as diversified development and production in the arms, chemical, urban development, architecture, transportation, appliance, and personal luxury goods industries have caused increased economic development and competition, and product life cycles have been deliberately shortened in an effort to fulfill materialistic yet nonessential demands among families and individuals. In addition to the environmental pollution caused by the considerable amount of waste produced as a consequence of economic activity, the development and production of components downstream, midstream, and upstream have also accelerated continually. This has led to excessive mining and considerable energy demand, resulting in more serious environmental pollution. High energy consumption is the main reason for high CO_2 emissions and global warming. The aforementioned reasons indicate that pollution and warming are problems caused by an overemphasis on economic prosperity and materialism. Countries globally recognized the severity of the natural crisis at the Copenhagen Summit in 2009, and each country submitted an Intended Nationally Determined Contribution (INDC) according to the Paris Agreement and agreed to set a future goal of endeavoring to limit temperature rises to under 2 °C or 1.5 °C. However, to facilitate reaching an agreement at the time, the conference adopted a flexibility principle: specifically, only general goals were set, and methods and details of implementation were not thoroughly discussed. Therefore, the Conference of the Parties (COP) 24 is the key to whether the Paris Agreement can be implemented [12]. If humans do not have sufficient awareness and conscientiousness, civilization and technological advancement could ultimately cause damage to the Earth through a vicious circle.

The aforementioned discussions indicate that the future control of global warming is determined by INDCs [12]. Cities are foundational sites of development and crucial basic units. Therefore, various problems, such as environmental disasters, pollution, and ecological damage caused by city development, should be reduced. To promote the sustainable development of the urban environment, the use of new energy must gradually replace the use of natural energy. Additionally, the industrial, housing, and transportation sectors must all increase their percentage of new energy used annually. Environmentally friendly methods must be implemented in public construction projects to reduce the environmental effects and ecological damage of construction. Destek and Sarkodie [13] suggested that climate change has become a global phenomenon because of its threat to sustainable development. Therefore, creating low-carbon ecocities should be a priority. Relevant policies should be developed with strict implementation, while green community construction, environmental campaigns, and education for community residents should be further strengthened [11]. Residents should be encouraged to participate in green community activities and volunteer work. This can cultivate pro-environmental consciousness [1], involving a belief in the principles of environmental protection, the value of biodiversity, and energy-conserving daily life habits. We used two sets of methodologies, the Delphi method and fuzzy logic theory, to investigate multicriteria decision-making models for low-carbon ecocity construction. Our objective was to provide an auxiliary evaluation method for low-carbon ecocity governance that would enable scientific quantitative evaluation during the process of urban development and elucidate the effectiveness, advantages, and disadvantages of devoting efforts to low-carbon ecological development. Finally, this can help cities to achieve the goal of developing green energy and preserving the natural environment.

2. Literature Review

Cities in every country are developing in the direction of green energy and ecological stewardship. This embodies a mission and a shared responsibility for exploiting the Earth's natural resources sustainably. This mission is arduous, and obtaining agreement from each country is highly difficult. This is because developed, developing, and undeveloped countries do not have the same foundation for economic development. Moreover, in light of the macroeconomic development needs of each country and the increasingly strong competition between them, reaching a compromise on CO_2 emissions has become more difficult. Because economic development depends on energy consumption and a complex energy production and distribution system affected by socioeconomic factors [14], appropriately handling the relationship between economic development and energy consumption is not simple. Energy is a necessity for various industries and is indispensable in the daily lives of the majority of humans. Considerable CO_2 emissions and global warming problems have been caused by the excessive energy extraction and consumption of humans. Humankind now faces a self-inflicted crisis that places our species on the brink of decline and extinction. This is because the natural environment can no longer endure further damage, and climate change is perhaps a warning from nature. However, there is still time to alleviate global warming and reduce environmental damage if we reduce our level of energy consumption and CO_2 emissions and pay close attention to the biocapacity of the Earth. The construction of a low-carbon and ecologically friendly environment is the foundation for sustainable cities. However, the development of low-carbon and ecologically designed cities remains in the nascent stage of campaigning and promotion because of multiple factors; concurrently, a consistent understanding of the issue by the management of most cities has not yet been reached for the implementation of such cities. Cities with large populations and high energy consumption are the core of national economies and are prone to ecological deficits. Therefore, understanding factors that affect urban development is necessary before implementing city governance.

2.1. Description of Preliminary Criteria Influencing Low-Carbon City Development

The crises of global energy consumption, CO_2 emissions, environmental and ecological damage, and climate change have induced a complex problem that entails continual environmental deterioration. This problem has become the issue that receives the most attention globally. However, prioritizing economic development, national sovereignty, technological advancements, and the material standard of living of their citizens are ways in which countries undermine the global need to solve environmental problems. These factors are also the main reasons for high energy consumption and the failure to reach a global agreement on reducing CO_2 emissions. Cities are the main energy users and greenhouse gas emitters; thus, they are the key to alleviating climate change [15]. Therefore, the development of low-carbon cities must entail a low-carbon economic base; that is, the use of low-carbon energy sources such as renewable energy, wind energy, and photovoltaic storage systems [16] in industrial production is necessary. The goal is to reduce the CO_2 emissions of industrial production and reduce pollution and energy consumption. An increasing number of scholars have paid attention to low-carbon economy research in recent years [10,17,18]. A white paper by the government of the United Kingdom proposed a low-carbon economy as a goal in 2003 and aimed at reducing mid- and long-term CO_2 emissions in 2020 and 2050, with the latter being a reduction of 60% of the emissions from 1990.

The low-carbon economy has received a great deal of attention in most countries, and low-carbon transitional development has been implemented in high energy-consuming areas such as the industrial, transportation, and housing sectors [10,18]. For example, China and India have focused their efforts in the technical and creative fields. The two countries have simultaneously and successfully made advances in terms of low-carbon development, but to different extents [19]. China has established a time by which the full use of new-energy cars and buses must be implemented in most cities, and buses in most cities are currently using new energy. Gaps exist between economic development and governance policies in various cities. Nevertheless, because economic development and governance policies vary between cities in different regions, with respect to low-carbon development, more emphasis should be placed on reducing CO_2 emissions per capita and improving the implementation of green design during urban construction [20]. The root of environmental pollution is people; therefore, constructing low-carbon cities is of great importance for cultivating low-carbon living habits in individuals and families and is also a social responsibility that every individual ought to fulfill. This would help cities to implement low-carbon economies and sustainable development strategies.

2.2. Description of Preliminary Influencing Criteria of Ecocity Development

The developmental trend of ecocities entails concerns for ecosystem services, ecological footprints, ecological niches, landscape patterns, ecological residences, and ecological tourism. Rapid and large-scale urbanization has led to changes in land use, which has influenced ecosystem services. Specifically, the relationship between urbanization and ecological system services is determined not only by the characteristics of a study area; the relationship is also closely related to the type of ecological system services selected and indicators used to measure urbanization [21]. Human activities gradually cause unbearable pressure on the environment and simultaneously undermine an ecosystem's ability to provide ecological services [22]. Making an overall evaluation of complex ecosystem services is not easy; nevertheless, understanding aspects of ecosystem services by adopting clear angles and seeking transparent and easily comprehensible evaluative methods may yield effective information for solving specific environmental problems [23]. For example, Ryfield et al. [24] studied geolocation as a type of material phenomenon to demonstrate the relationship between the ecological conditions of specific locations and the cultural conditions of the societies in which humans live. The researchers incorporated a "cultural value of the coastline" project and studied the cultural contribution of materialism research, and these efforts yielded a mechanism for making classifications within an ecosystem services framework [24]. Ecosystem services exhibit diversity and variety, and in terms of ecocity development, they are a crucial method for investigating sustainable consumption and the sustainable development of cities.

According to changes in the global ecological footprint and biocapacity investigated between 1961 and 2012 by Zhang et al. [25], the global ecological footprint increased from 2.28 gha (global hectare) in 1961 to 2.84 gha in 2012, representing a total increase of 0.56 gha. A considerable change was observed in terms of biocapacity, which changed from 3.14 gha in 1961 to 1.73 gha in 2012, representing a total decrease of 1.41 gha. In 2012, the global ecological deficit reached approximately 1.11 gha, and this is closely related to the global problems of technological advancement, high CO_2 emissions, environmental pollution, and climate change. The ecological deficit is also caused by the rapid increase in global population and the failure of countries to reach an agreement to combat climate change. The prosperity evident in human living conditions and technological advancement has caused the global ecological deficit.

The daily lives of humans, various types of activities (e.g., industry, business, agriculture, fishing, and animal husbandry), and urban–rural development gaps are usually affected by policy and economic development. For example, Peng et al. [26] proposed that the ecological deficit of cultivated land was generally large due to poor public land use planning, and strengthening ecological restoration efforts could help to reduce ecological deficits. Cities with greater ecological deficits of cultivated land and economic development in cities both have positive and negative effects on climate change and sustainable development. A negative causal relationship exists between economic growth and ecological footprints [13]. Moreover, large cities tend to have large ecological deficits, extremely large ecological footprints, and poor coordination between ecological and economic systems, all of which entails considerable ecological challenges [27]. Cities have features such as advanced public facilities, comprehensive medical and service institutions, and job opportunities that exceed those of adjacent villages and towns, and these features tend to attract people from elsewhere. This leads to various problems in cities such as high population density, overdevelopment, high energy consumption, high pollution, high housing density, traffic congestion, and difficult city governance. Cities not only require a larger ecological footprint per capita, but are also areas with more serious ecological deficits. Therefore, most cities face pressure to develop ecologically friendly improvements and undertake sustainable ecological development.

The previous sections indicate that preliminary criteria related to the construction of low-carbon ecocities can be separated into the following 17 items: policy and governance, low-carbon development, low-carbon economy, low CO_2 emissions, low pollution, low energy consumption, low-carbon living habits, individual social responsibility, ecosystem services, ecological footprints, ecological niches, landscape patterns, ecological residence, ecological tourism, biocapacity, and ecological deficits or reserves. These criteria make it clear that the intention to construct a low-carbon ecocity entails the reconstruction of a city's overall life system and cannot be achieved within a short time.

3. Materials and Methods

This study combined the expert group decision-making of the Delphi method and functions of quantification and the fuzzy linguistic decision-making of fuzzy logic theory. The aim was to create a multicriteria decision-making evaluation model for low-carbon ecocities. The two methodologies and research design are described in the following.

3.1. Delphi Method and Fuzzy Logic Theory

Hsueh [5] contended that the Delphi method is the best approach for obtaining the latest professional knowledge from expert groups—knowledge that is beneficial for increasing research reliability. The Delphi method comprises the following steps: (1) select experts, (2) obtain initial assessment factors from previous studies, (3) design and distribute questionnaires, (4) recover and modify questionnaires, (5) return to Step 4 if assessment factors do not reach a consensus, and (6) obtain the criteria required for the study [5]. A flowchart of the Delphi expert survey is shown in Figure 2. The Delphi method is an anonymous expert questionnaire survey method. In 1946, the RAND Corporation, an American company, first used the Delphi method to predict the future development of the company. Today, the method is widely used in various domains. For example, the Delphi method is used to discuss energy issues [28], urban environmental quality [29], future goods transport [30], protection of the Amazon rainforest [31], and issues in medical fields [32].

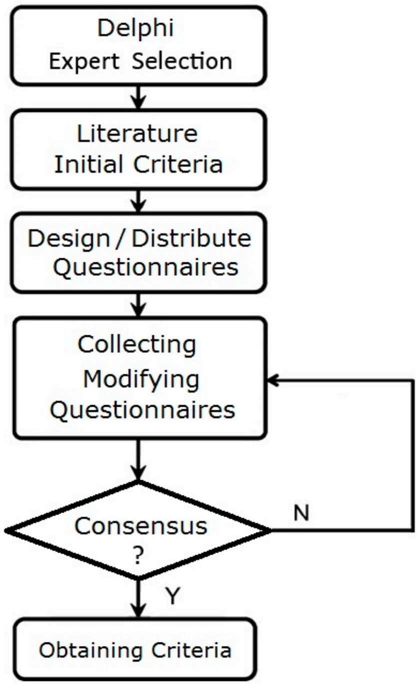

Figure 2. Flowchart of Delphi expert survey.

Fuzzy logic theory entails the calculation of ambiguous semantics of humans [33]. Hsueh [5] suggested that in the quantification procedure of fuzzy logic, fuzzy sets [34], a membership function, and quantified interval values of each criterion must first be constructed. After the construction of a fuzzy logic inference system (FLIS) is completed, the FLIS exhibits the functions of inference and an algorithm. The quantitative evaluation algorithm of the FLIS can be separated into four procedures: (1) an input value, which can be quantified values or ambiguous semantics of different units; (2) a fuzzifier; (3) rule-based inferences to the defuzzifier; and (4) output value quantification. The FLIS is a scientific artificial algorithm that can accept different units, scales, and nonquantified and unclear semantics. Thus, it is an algorithm that cannot be replaced by normal mathematical equations. Fuzzy logic theory is a methodology, first proposed by Zadeh in 1965, that is widely applied in various domains today. For example, it has been applied in the following domains: corporate sustainable performance assessment [35], groundwater contamination estimation [36], hydrothermal process assessment [37], habitat ecological integrity and environmental impact assessment [38], renewable energy system assessment [39], and agricultural soil dynamic quality index assessment [40].

The range of studies that have successfully combined the Delphi method and fuzzy logic theory is extremely broad and includes the following topics: green community construction and energy conservation [1,5], sustainable ecotourism indicators [41], identification of financial barriers to energy efficiency [42], and optimal siting of charging stations for electric vehicles [43].

3.2. Research Using the Delphi Method and Fuzzy Logic Theory

The Delphi method research design involved inviting 12 Delphi experts, including chief executive officers (CEOs) in the business world, senior executive officers in management departments, and senior professors in academia. All of them had more than 15 years of practical experience in urban planning. We used the 17 preliminary criteria introduced in the previous section as the basis for designing the first Delphi questionnaire survey. Following three surveys [44], all 12 experts agreed on four crucial criteria when evaluating the construction of a low-carbon ecocity: policy norms, resident cooperation, pollution prevention and control, and ecological reserves.

In terms of fuzzy logic theory research design, this study consulted the opinions of Delphi experts in the process of constructing the FLIS. Relevant required parameter definitions of the Delphi–fuzzy (DFuzzy) model included the following: (1) Fuzzy sets: each criterion was set as three scenarios (high, medium, and low or good, ordinary, and poor). The four criteria could be combined into a total of 81 evaluation scenarios. (2) Membership function (MF): the commonly used Gauss–MF and Tri–MF were adopted. (3) Quantified interval values and units of each criterion and the DFuzzy model's overall quantified evaluation diagram are shown in Figure 3. The steps of the model's quantification process were sequenced as follows: input scenarios, apply a fuzzifier, apply a defuzzifier, and output the value. A total of 81 evaluation scenarios existed, and thus 81 scenario combinations of quantified evaluation can be applied to cities. Definitions of the relevant parameters of the DFuzzy model are shown in Table 1.

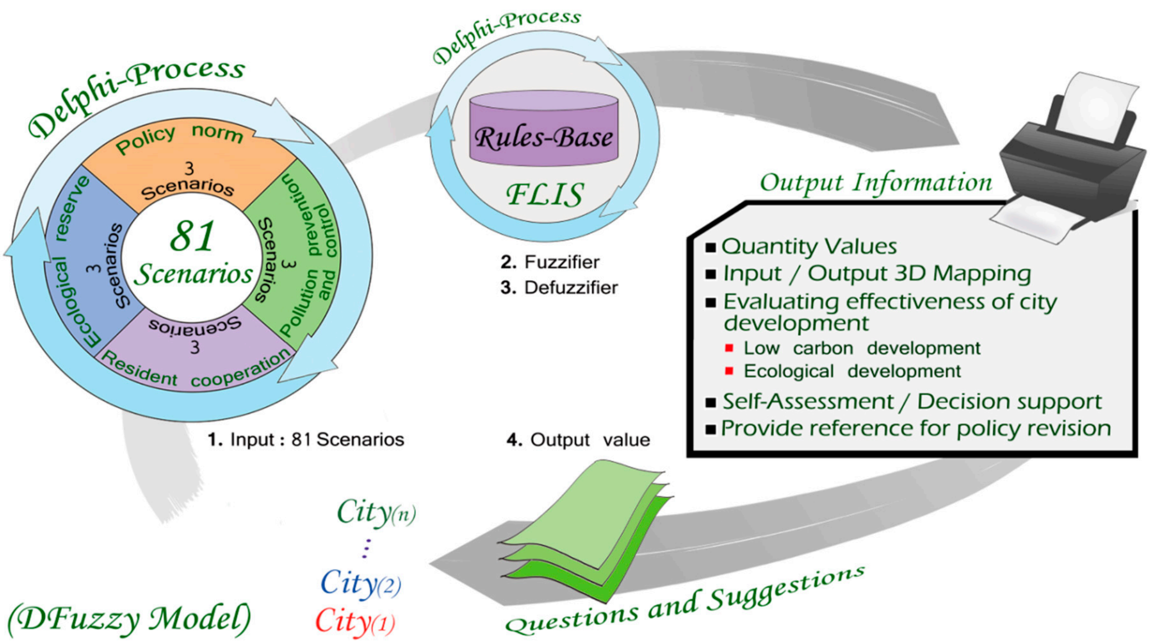

Figure 3. Overall quantification of DFuzzy model. FLIS: fuzzy logic inference system.

The parameter definitions in Table 1 were agreed upon by all the experts through the Delphi process, and the four criteria were defined in detail as follows: (1) three fuzzy sets of qualitative comparative analysis [45,46]: the semantics were defined as "Rigorous," "Ordinary," and "No," and the fuzzy range was defined as being between 0% and 100%; (2) three fuzzy sets of resident cooperation: the semantics were defined as "Good," "Ordinary," and "Poor," and the fuzzy range was defined as being between 0 and 100%; (3) three fuzzy sets of pollution prevention and control: the semantics were defined as "Good," "Ordinary," and "Poor," and the fuzzy range was defined as being between −30% and 50% and was used to show the completeness of improvement goals; (4) three fuzzy sets of ecological reserve: the semantics were defined as "High," "Medium," and "Low", and the fuzzy range was defined as between −10 and 10 times. It was used to show the number of times that the biocapacity was larger than ecological reserve obtained by ecological footprints. A larger ecological reserve is more desirable. The measurement scale defined in fuzzy logic is an artificially defined fuzzy scale. For example, in the resident cooperation degree, "0" means Poor, "50" means Ordinary, and "100" means Good". However, is "70" Good or Ordinary? Is "30" Poor or Ordinary? The inference of fuzzy logic is to define the degree by membership functions and finally perform defuzzification through FLIS. The results of the quantized value output are included in this manuscript.

Table 1. Definitions of relevant parameters of the DFuzzy model.

Input Scenarios			Fuzzy Output Value (Quantitative Value)	
Criteria	**Fuzzy Sets**	**Fuzzy Range**	**Membership Function (MF)**	**Fuzzy Sets**
Policy norm	Rigorous Ordinary No	0–100%	Gauss–MF Tri–MF	Very good Good Ordinary Poor Very poor
Resident cooperation	Good Ordinary Poor	0–100%	Gauss–MF Tri–MF	
Pollution prevention and control	Good Ordinary Poor	−30% to 50%	Gauss–MF Tri–MF	
Ecological reserve	High Medium Low	−10 to 10 times	Gauss–MF Tri–MF	

4. Model Overview and Dfuzzy Model Application

After defining the parameters of the DFuzzy model and constructing the if–then rules base, the FLIS has functions of the quantified inference and the algorithm. The DFuzzy model is a multicriteria decision-making evaluation model with a high degree of objectivity.

4.1. Model Overview

A diagram of the calculation of quantification of the fuzzy model is presented in Figure 4, and its relevant parameters are shown in Table 1. A 3D mapping diagram of input criteria and output quantitative values is shown in Figure 5. The DFuzzy model's overall quantitative evaluation diagram is depicted in Figure 1 and illustrates that the model has 81 scenario evaluation combinations. The rule base of the FLIS is similar to a human brain, and the input scenarios can be converted to quantitative output values through the processing procedure using a fuzzifier and defuzzifier. The DFuzzy model can simultaneously accept unclear and ambiguous semantics, different units, and different measurement interval values. The 3D mapping input and output elucidated mutual relationships between criteria.

Figure 5 shows the 81 input evaluation combinations of the four criteria. After an inference calculation of FLIS's AI, the input evaluation combination is converted into a 3D relational diagram of the quantized output. The relationship between the two input criteria (policy norm and resident cooperation) presented in Figure 5a and corresponding quantitative values reveal that, regardless of the strictness of the policy norm requirement, the effect is limited if residents do not have a strong willingness to cooperate. When the willingness of residents is more than 50%, the corresponding quantitative values increase markedly. Moreover, Figure 5b,c illustrate that when the policy norm gradually reaches the goal of pollution prevention and control, the ecological reserve also increases gradually.

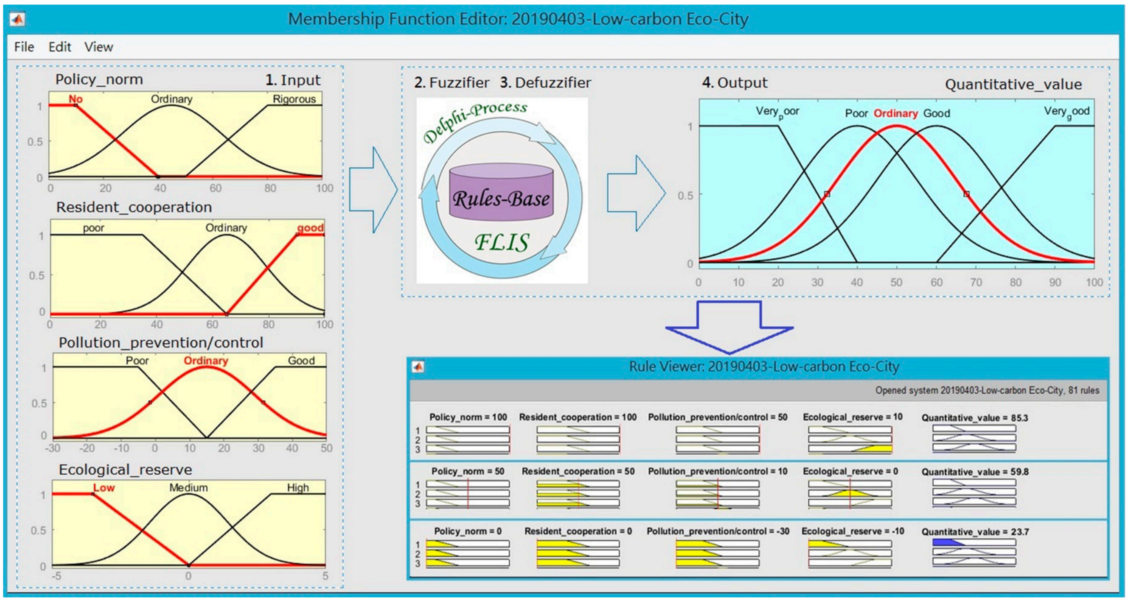

Figure 4. Quantitative calculation of DFuzzy model.

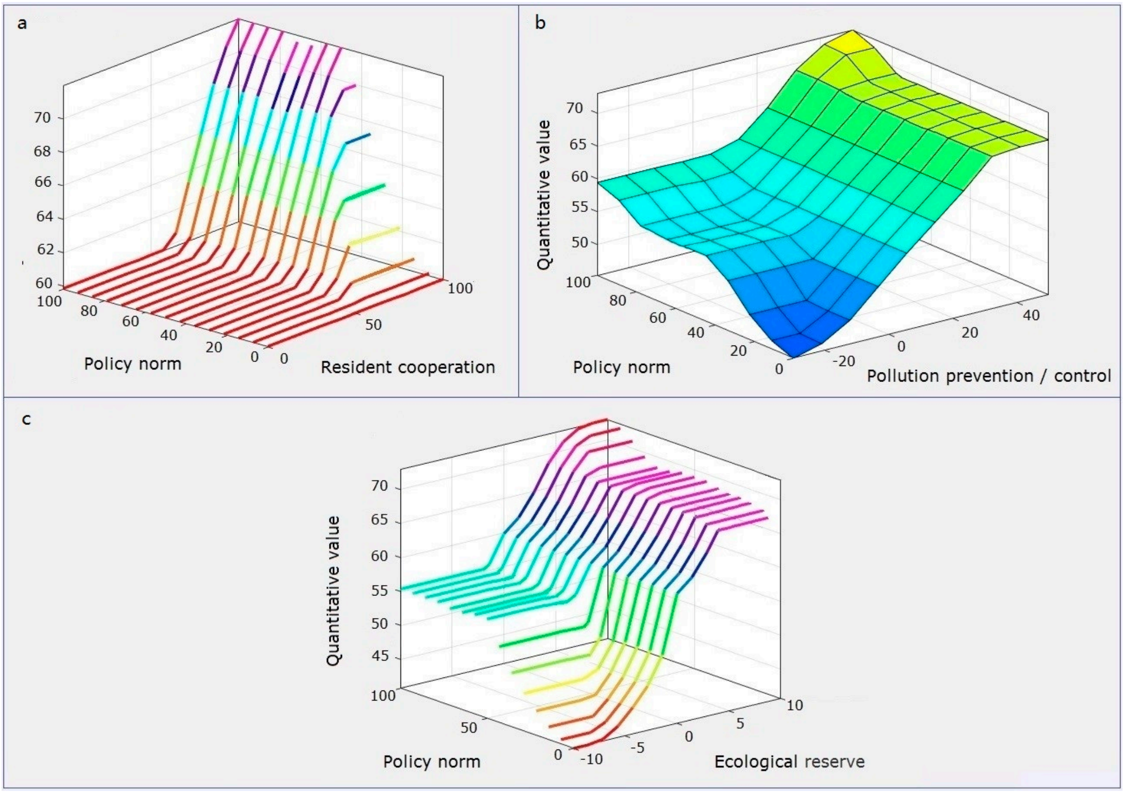

Figure 5. Three-dimensional mapping of input criteria and quantitative output values. (**a**) policy norm-resident cooperation, (**b**) policy norm-pollution prevention/control, (**c**) policy norm-ecological reserve.

4.2. Application of the DFuzzy Model

Zadeh [31] suggested that fuzzy logic has the function of computing with words. Specifically, it conducts the quantitative processing of the natural language of humans. The DFuzzy model constructed in this study has functions of qualitative and quantitative analysis. In terms of practical evaluation, three types of low-carbon ecocity (optimal, general, and worst cases) were used to explain the quantitative calculation function of the model. Evaluation combinations of the three case scenarios are shown in Table 2. The quantitative evaluation of the DFuzzy model indicates that the optimal, general, and worst quantitative output values of a low-carbon ecocity were 85.3, 59.8 and 23.7, respectively. A diagram of the application is shown in Figure 6.

Table 2. Application of DFuzzy model to evaluate optimal, general, and worst quantitative output values of a low-carbon ecocity.

Input Scenario	Optimum Case	General Case	Worst Case
Policy norm	Rigorous (100)	Ordinary (50)	No (0)
Resident cooperation	Good (100)	Ordinary (50)	Poor (0)
Pollution prevention and control	Good (50)	Ordinary (10)	Poor (−30)
Ecological reserve	High (10)	Medium (0)	Low (−10)
Output value	85.3	59.8	23.7

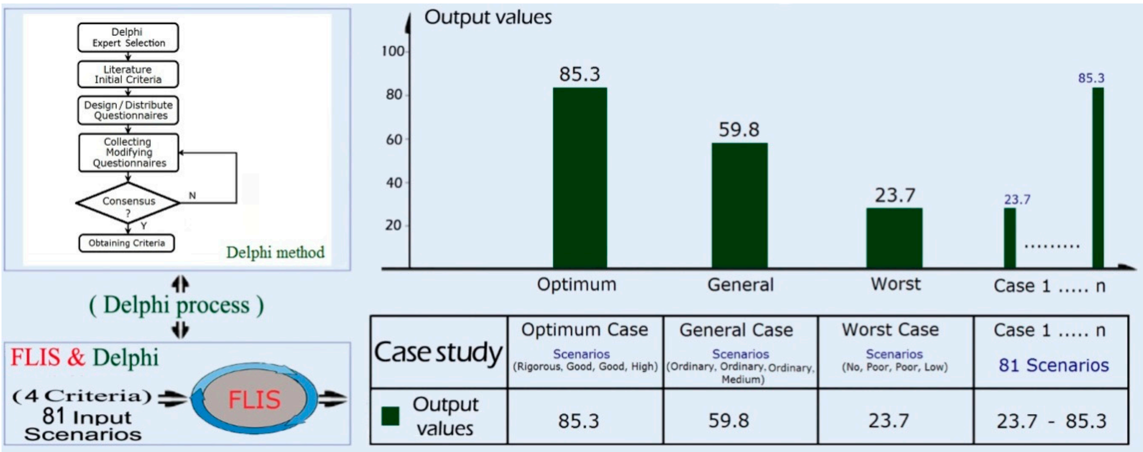

Figure 6. Diagram of DFuzzy model application.

5. Results and Discussions (Case Study)

There are four criteria in the DFuzzy model evaluating the development of a low-carbon ecocity, each of which contains three kinds of scenarios, constituting 81 groups for assessing the input scenario. The input scenario of each group could be quantized values or imprecise semantics in natural language, such as high (good), medium (general), low (bad), etc., because the model has the function of calculating imprecise semantics. The practical application of the DFuzzy model took three areas as examples: Baiyun District of Guangzhou City, Guangdong Province; Conghua District of Guangzhou City; and Dahu Community of Kaohsiung City, Taiwan, which verified the objective evaluation function of the model. Table 3 describes an overview of these three areas. The assessed input scenarios of Baiyun District, Conghua District, and Dahu Community obtained consensus of the experts through a two-round Delphi process. The input scenarios are shown in Table 4. The quantified output values evaluated by the DFuzzy model were 70 points for Beiyun, 83.8 for Conghua, and 81.4 for Dahu Community. Figure 7 indicates the DFuzzy quantitative comparison values of development of low-carbon ecocities in this study.

Table 3. Overview of characteristics of Baiyun District, Conghua District, and Dahu Community.

Area	Features Overview
Baiyun, Guangzhou	Baiyun District is one of the more industrialized areas in Guangzhou. The current policy restricts the entry and investment of polluting industries and formulates a schedule for the improvement and outward migration of polluting industries. This district is densely populated, and some of the inhabitants are out-of-town workers from inland towns and villages who have poor awareness of and ability to recognize urban low-carbon and eco-development (the relevant policy focus is on low-carbon environmentally friendly cities, ecological civilization construction, energy conservation and carbon reduction, and low-carbon industries).
Conghua, Guangzhou	Conghua District, an important water source in Guangzhou, is under strict regulation and protection by policies and edicts and focuses on the development of green and pollution-free industries, with severe restrictions of entry and investment in polluting industries. Residents have high environmental awareness and recognition of urban low-carbon and eco-development. Furthermore, Conghua is a key index town listed in national developing ecological cities. (the relevant policy focus is on low-carbon environmentally friendly cities, ecological civilization construction, development of national key ecological towns, development of energy industry, and green tourism).
Dahu Community, Kaohsiung	Dahu Community ranked first in the appraisal through the comparison of the overall construction of green communities in Kaohsiung City in 2018 and in Taiwan, and has many environmental lecturers and volunteers. The residents have high environmental awareness. Overall, green construction was achieved based on years of promulgation and guidance led by the Community Development Association; thus, residents have a high recognition of low-carbon and ecological development. However, this area does not have special protection and development assistance (the relevant policy focus is on overall green community construction, environmental lecturers, environmental volunteers, afforestation, solar power generation, and millions in subsidies for solar roofing).

Table 4. Delphi experts' consensus for the input scenario of the three areas.

Input Scenario	Baiyun	Conghua	Dahu Community
Policy norm	70	100	70
Resident cooperation	30	90	90
Pollution prevention and control	30	45	45
Ecological reserve	6	8	8
Output value	70	83.8	81.4

The DFuzzy model is a quantitative tool that is good at dealing with multiple attributes and capable of accepting different data attributes, allowing inaccuracies, and accepting the ambiguous and natural meanings of decision-makers (evaluators), which is difficult to accomplish by traditional mathematics. Moreover, the Delphi experts who established the DFuzzy model process provided research assistance in group decision-making, enabling the model to be highly objective and adaptive; thus, it can evaluate a single city or multiple cities simultaneously. The results and discussions of this study are described in the following sections. The excessive extraction and use of energy have caused high global CO_2 emissions and uncontrolled climate change. This not only endangers biodiversity but also puts human lives and property at risk. Global climate change conferences have consistently failed to reach an agreement to reduce CO_2 emissions. The opportunity to alleviate the irreversible crisis of climate change can only be capitalized upon if every country implements new energy policies that propose goals to reduce CO_2 emissions on their own. Individuals, families, towns and villages, and countries can determine the emissions of an individual or a country through the use of calculators of CO_2 emissions and ecological footprints. These can help us to acquire knowledge of the current conditions of ecological footprints, biocapacity, ecological deficits, and the ecological reserves of one's region. The data provided by the calculators can also help to elucidate a reference framework regarding the amount of CO_2 produced, the biocapacity, and ecological deficits. Climate change is caused by industrial development and various competitions and needs of humans. Because countries emphasize overall economic conditions and individuals emphasize materialistic desires and consumption habits, and it is uncertain when and where climate change disasters will strike, the public cannot easily perceive the catastrophic consequences of climate change. Nevertheless, cooperation among residents is crucial regarding the overall development of low-carbon ecocities.

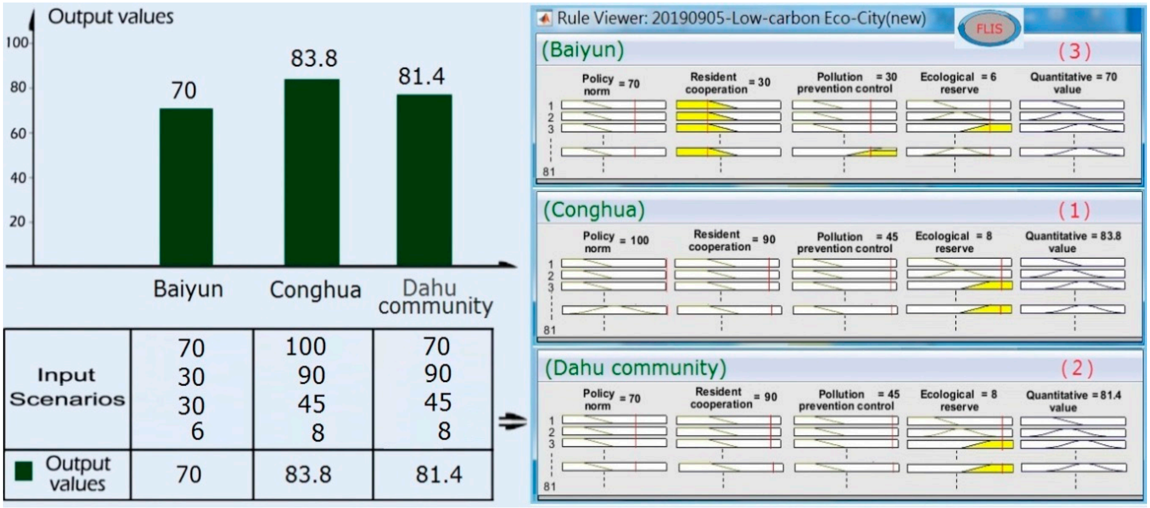

Figure 7. DFuzzy quantitative comparison of the development of low-carbon ecocities in Baiyun, Guangzhou; Conghua, Guangzhou; and Dahu Community, Kaohsiung.

This study compiled 17 criteria that influence low-carbon ecocities. We achieved agreement from 12 experts using the Delphi process on the importance of four criteria: policy norms, resident cooperation, pollution prevention and control, and ecological reserves. Further verification through the Delphi process indicated that the four criteria had a total of 81 types of evaluation scenarios. This study combined the Delphi method and fuzzy logic theory to construct the DFuzzy model. The proposed model has functions by which it performs qualitative and quantitative analysis as well as a scientific quantitative calculation function, high objectivity, and adaptability, the latter of which is convenient for later maintenance and use. Cases of DFuzzy model application suggest that it cannot only evaluate the current low-carbon and ecological conditions of a city but also simultaneously make comparisons between cities and elucidate priorities of developing low-carbon ecocities.

6. Conclusions

Sustainability is a global issue calling for better solutions to the industries, built environment, and urban planning and development. Previous studies have addressed the concept of ecocities, and some relevant models have been proposed. However, the development of low-carbon cities and ecocities is often discussed separately, while a model for evaluating the development of low-carbon ecocities is proposed in the study as an integrated approach. Thus, we present some advices with the expectation of promoting low-carbon ecocities. Compared with previous studies, this paper proposes an integrated approach and operational decision-making model to support the development of low-carbon ecocities, which is a complimentary contribution to the literature.

1. The Delphi method has the advantage of expert group decision-making, and fuzzy logic theory has the function of quantitative decision-making, which is a part of artificial intelligence. Therefore, the DFuzzy model established by integrating the two methodologies is a set of multiattribute modes to evaluate decisions with high objectivity, adaptivity, and scientific quantification.
2. In terms of the three areas, although Guangzhou has a number of environmental regulations and low-carbon development plans, such as low-carbon environmentally friendly cities, ecological civilization construction, energy conservation and carbon reduction, green building operations, and low-carbon industries, there are still old polluting industries in Baiyun within the grace period of factory relocation and restricted improvement. Nevertheless, Conghua, also a key ecological development area, promoted the World Eco-Design Conference in December 2108, thereby contributing to raising local residents' awareness and recognition of ecological development and encouraging them to participate in it. In addition, in the appraisal, by comparing the overall construction of green communities in 2018, the Dahu Community of Kaohsiung City gained first place in Kaohsiung City and second in Taiwan. Although the group organization was the main force promoting ecological rehabilitation, environmental lecturers, environmental volunteers, green community transformation, and air quality renovation and residents have a high environmental consensus, the quantitative value of the DFuzzy model evaluation is lower than that of Conghua, because the sustainability and normative power of private organizations' investment funds is far less than the influence promoted by government policies.
3. There are four macro factors affecting the development of low-carbon ecocities: policy norms, resident cooperation, pollution prevention and control, and ecological reserves. As mentioned in point 2 above, on the condition that governments are willing to sacrifice some of their economic interests, the development of low-carbon ecocities will be efficient, as in the Conghua District of Guangzhou. In addition, low-carbon ecocities can be built by means of the overall construction of green communities, as in the Dahu Community in Kaohsiung City.
4. As of 2019, Arctic ice is melting increasingly quickly, and worldwide greenhouse gas emissions are as high as before, increasing climate anomalies. Increasingly severe natural phenomena are occurring, but they are still not as vital as economic development for some industrial countries, which hampers the reaching of a global climate agreement related to the reduction of CO_2 emissions.

The global environment continues to deteriorate and global society is calling for better thoughts and actions. While this paper offers scientific case studies to demonstrate the integrated approach in supporting the development of ecocities, there are still some limitations and challenges for future studies. Perspectives from diverse experts and specialized investigations with other meaningful case studies would be a good extension as well as comparative studies to explore ways that improve ecocities developments. Criteria and the hierarchy of decision rules could also be reviewed for research topics with different structures.

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