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Decision-Making Model Based on Discriminant Analysis Fuzzy Method for Low-Carbon and Eco-Friendly Residence Design: Case Study of Conghua District, Guangzhou, China

Sung-Lin Hsueh [1], Yue Sun [1], Yihang Zhang [1], Nan Xiao [1] and Teen-Hang Meen [2,*]

[1] Department of Art Design and Creative Industry, Nanfang College, Guangzhou 882, Wenquan Road, Conghua, Guangzhou 510970, China; hsueh.sl@msa.hinet.net (S.-L.H.); sinyocn@gmail.com (Y.S.); zyihangyh@outlook.com (Y.Z.); xiaonan05200@outlook.com (N.X.)

[2] Department of Electronic Engineering, National Formosa University, Huwei 632, Yunlin, Taiwan

* Correspondence: thmeen@gs.nfu.edu.tw

Abstract: Many countries aim to promote low-carbon and eco-friendly development and find a route to sustainable development. For such development, a model that helps design and build appropriate constructions is necessary. Thus, this study is carried out to establish such a model by combining the Delphi method, analytical hierarchy process (AHP), and fuzzy logic theory (FLT) (DAFuzzy model). In the Delphi method, the expert's opinions are reflected in three dimensions (green facilities, ecological facilities, and community participation) and nine factors (green building materials, photovoltaic power generation, energy-saving equipment (green facilities), green roof, planting/vegetation, rainwater collection/water recycling (ecological facilities), subsidies, resident participation, appropriate norms (community participation)). Then, AHP is used to calculate the relative weight of each factor. Finally, by using FLT, the output value of each factor is calculated to find out the best scenarios and influencing factors for the scenario. The result shows that green facilities are the most important dimension, followed by community participation and ecological facilities. Among 45 different scenarios for the model, the best is to consider green facilities and ecological facilities with community participation. The important factors in the best scenario include photovoltaic power generation, planting/vegetation, energy-saving equipment, green building materials, appropriate norms, rainwater collection/water recycling, subsidies, and green roof. The proposed model is validated with residential houses in Conghua District, Guangzhou city, China. Considering the dimensions and factors of the best scenario, the proposed DAFuzzy model proves that a low-carbon and eco-friendly development requires support with appropriate policies and a large investment. The research result suggests that building a low-carbon and eco-friendly house needs the support of the government and people's understanding and participation in eco-friendly development.

Keywords: community building; low carbon; eco-friendly development; Delphi method; analytical hierarchy process (AHP); fuzzy logic theory (FLT); artificial intelligence (AI)

Citation: Hsueh, S.-L.; Sun, Y.; Zhang, Y.; Xiao, N.; Meen, T.-H. Decision-Making Model Based on Discriminant Analysis Fuzzy Method for Low-Carbon and Eco-Friendly Residence Design: Case Study of Conghua District, Guangzhou, China. *Buildings* **2022**, *12*, 815. https://doi.org/10.3390/buildings12060815

Academic Editor: Audrius Banaitis

Received: 1 May 2022
Accepted: 8 June 2022
Published: 13 June 2022

1. Introduction

At present, the world is facing a severe challenge from climate change that is mainly brought by environmental damage. Lynas stated that Greenland would experience an irreversible ice-melting stage when the global temperature increases by 1.2 °C [1]. Global warming caused by the greenhouse effect from the high emission of CO_2 contributes to the sea-level rise caused by ice melting. The rise of the sea level will affect residents along and near the coastal areas. The greenhouse effect also causes environmental damages that have been researched continuously [2]. However, the degree of the damage seems to worsen with the increase of torrential rainfall, typhoons, and hurricanes which cause floods and mudslides. Increased wildfires with anomalous rainfall and snowfall also affect the climate, along with permafrost thawing [3].

Although countries are establishing policies to mitigate damages from climate change and reduce energy consumption and CO_2 emission from the use of fossil fuels, there have not been perfect solutions yet, as fossil fuel use is still critical to the economy and politics of many countries. However, it is not easy to change an economic structure in which there are many energy-intensive industries. Traditional manufacturing, supply chains, transportation, and construction belong to such energy-intensive industries, and it is not easy at all to decrease their energy consumption. It is also difficult for a country to change its industrial structure in a short time. When new energy policies are implemented, they influence industries significantly and have significant impacts on the overall economy and development of countries. Therefore, residential areas and buildings have been paid attention to as they also cause pollution, consume much energy, and damage the environment. Besides, it is easy for households to implement green energy use and low carbon lifestyles by residing in low-carbon houses and eco-houses for the protection of the environment and sustainable development [4,5].

Thus, a positive approach is required for households to emit less carbon to protect the environment. For this, the planning, design, and construction of eco-friendly residential areas and buildings will encourage overall efforts for sustainable development. This is thee driving force for the sustainable development of the community. For low-carbon life and ecological protection, we propose a new model for designing buildings using the concepts of people, culture, land, scenery, and production for a green and eco-friendly environment which harmonizes with environmentally-friendly concepts of food, clothes, transportation, and recreation. Such a design will also help to achieve the advantages of carbon neutrality [6].

Therefore, we propose a new model for designing residential buildings to realize pro-environmental action by considering the concepts 'green' and 'eco-friendly'. New buildings with such concepts will encourage residents to have an eco-friendly way of life and the community to adopt sustainable development. The residents can campaigning for the renovation of houses and the protection of the environment using their own experiences [7,8]. As it is not easy to change living habits, the design of buildings needs to consider the acceptability of energy policy for enhancing the eco-friendly development of lifestyle and communities [9].

The new model is established based on the combination of the Delphi method, analytical hierarchy process (AHP), and fuzzy logic theory (FLT). The proposed model allows the creation of a policy with a theoretical background and adequate decision-making [7,9–11]. Thus, the model helps decision-makers easily understand the eco-friendly development of the community based on quantitative measures. The result of this study provides the basis for decision-making and a reference for policy management.

2. Literature Review

Buildings in Furukawa-machi in Japan are regarded as a successful case of eco-friendly construction. Furukawa is now a famous tourist spot but used to be notorious for its serious industrial pollution. For the promotion and arousal of residents' awareness of environmental protection, the Furukawa-machi community has focused on education, including on environmental protection, cultural protection and reuse [10,11]. A public organization was established by the community to manage their environment and propose related projects for the residents. As a result, all residents have abided by the environmental protection rule of the community which emphasizes sustainable living and lifestyle [12]. Their self-made regulation is a non-state policy created jointly by residents. It defines incentives and subsidies for the residents and includes detailed rules for the design of residential construction and repairs. The regulation was reviewed by the community's autonomous committee for customized and relevant specifications of construction or repair. Being coupled with the recognition of the residents and incentives for them, the regulation allows the community to develop diversely and sustainably. The community is known for its successful eco-friendly community construction in Japan.

The promotion of a low-carbon lifestyle and environmental protection is important. Different thoughts of policy-makers and residents hinder policies from being implemented. As a benefit, government subsidies encourage residents to accept eco-friendly policies to promote policy implementation [13]. For example, China has vigorously promoted its rural revitalization program in recent years to fill the gap between urban and rural development [14]. As the purpose of rural revitalization is to promote rural economic development and the return of population and industries in townships, the implementation strategy mainly focuses on subsidizing corporate investments, changes in rural areas, and cultural and eco-tourism. However, rural revitalization has changed the lifestyle of most residents and reduced indiscreet cultivation and development. At the same time, it has promoted green development. Conghua District in Guangzhou City is one example of rural revitalization [15]. Rural revitalization has been announced in the 14th five-year plan of the Central Committee of the Communist Party of China in 2021, which aims to accelerate the promotion of green development and construction [16].

Inappropriate land use has a serious impact on the natural environment. Development only with the aim of economic development may result in environmental damage [17]. The influence of changing hydrology and vegetation changes the landscape and damages the ecosystem [18]. The continuous expansion of human habitation with the construction of various facilities causes industrial pollution and deforestation [19,20]. The development and construction of tourist attractions and the reduction of agricultural areas also change the existing environment and affect biodiversity. Burnside proposed the use of eco-labels as sustainable efforts from agricultural producers. Eco-labels provide consumers with information about products and incentivize consumers and producers with additional prices [12]. Research on sustainability in ecological protection and restoration has been carried out on vegetation [21], sustainable living and lifestyle and consumers' social responsibilities and behavior [22], ecological restoration and biodiversity [23], ecological land-use planning [24], and ecological protection and restoration and its impact on ecological vulnerability [23].

- A household is responsible for energy consumption and is an important component of the community for implementing low-carbon living. Dependence between green and eco-friendly living brings about the best results. If industry and residents share the social responsibility toward green and eco-friendly living, the goal of sustainable development can be achieved. Eco-labels, green labels, and water-saving labels are commonly used in the construction industry in an effort towards sustainable development. The building or repairing of houses with the consideration of green and eco-friendly living contributes to the establishment of an eco-friendly community. The factors to be considered for the green residential building includes the following. [25] We defined the following factors after an extensive literature review for the design of the questionnaire using the Delphi method.
- For passive energy saving
  (1) Primary structure: insulated roof (thermal insulation), insulated exterior wall (thermal insulation), concrete floor (thermal dissipation), roof (shading),
  (2) Secondary structure: sunroof (lighting), a large number of windows (ventilation), low-E glass (thermal insulation), planation for shading, green roof (shading), ventilation design (5hermal dissipation & ventilation ball)
  (3) Equipment: rainwater storage system (water-saving), energy-saving light (power-saving), solar power panel, low VOCs' coating
- For proactive energy saving, the following energy-saving equipment is required: ventilation timer for a shower, temperature and humidity sensor, geothermal heat pump, adjustable boiler, mechanical ventilation system, split air conditioner, solar power system, programmable temperature controller, and a photovoltaic sensing system.

3. Methods

The Delphi method, AHP, and FLT are used to construct an auxiliary decision-making model to obtain the multiple attributes of low-carbon and eco-friendly residential design.

The Delphi method is used for experts' decision-making, and AHP and FLT are used for quantitative research. The Delphi method, AHP, and FLT are combined and used in this study.

3.1. Delphi Method

The Delphi method was first used by the RAND Corporation to predict the future development of the company. In the Delphi method, a questionnaire survey and/or direct interviews are adopted. After repeating the survey or interviews, a group decision by participating experts is obtained. The Delphi method has been used in various research such as the assessment of the sustainability of a building [26], creation of an evaluation index for low-carbon tourism [27], corporate reputation management model [28], decision-making and building consensus in pharmacy education [29], validation of wetland ecosystem assessment [30], application of agile methods in traditional logistics companies and startups [31], and sustainable management of buildings [32].

3.2. Analytical Hierarchy Process (AHP)

AHP is used to create a decision-making model with multiple attributes. It was proposed by Saaty as a research methodology for quantitative analysis [33,34]. AHP is used to evaluate a model by using the relative weight of each factor in the model in which factors are related to each other. Then, the factors are compared with others in a pairwise comparison matrix that is created from research data to calculate relative importance. The relative importance is divided into nine levels. When the relative importance satisfies the consistency index (CI) ≤ 1 and the consistency ratio (CR) ≤ 0.1, the model is validated to be effective, and the relative weights of the factors of the model are recognized to be valid. The weights are used as the reference for the verification of the decision-making.

As AHP allows decision-making with the consideration of multiple attributes, it is good for the analysis of decision-making with multiple influencing factors. AHP confirms the relative importance and ranking of evaluation factors and establishes a hierarchical sequence analysis model that is simpler than that of FLT. However, AHP only calculates the relative importance and ranking of each evaluation factor, and the actual quantitative value of each evaluation factor is not presented. Besides, the evaluation and analysis of multiple layers in decision-making can be time-consuming.

AHP is applied for selection of the best program among multiple evaluation programs, decision analysis and risk assessment, optimal allocation of resources, the establishment of a decision model with an evaluation program, performance evaluation, optimal design evaluation and conflict resolution, and loss reduction [35]. AHP has been adopted in various research works such as the selection of renewable energy in rural areas, green transition [36], multiple-criteria prioritization of seismic retrofit solutions in industrial buildings [37], confidence index and cloud model for rock slope stability evaluation [38], and urban green building planning [39].

3.3. Fuzzy Logic Theory (FLT)

FLT was proposed by Zadeh and changed the traditional concept of discontinuity of sets. A traditional set $\{0, 1\}$ has two elements, 0 and 1, but in a fuzzy set $\{0, 1\}$, an infinite number of elements are thought to be included. Fuzzy sets use the concept of membership function to deal with the vague semantics of humans. FLT is used for dealing with data that is not clarified, such as human ambiguity and image recognition. Zadeh proposed fuzzy logic to process human semantics for its quantification. FLT has been used in various fields of engineering technology and social humanities such as character recognition, robot control, automobile control, home appliance control, industrial instrument control, power control, signal and information processing, image processing, speech processing, data processing, database management, fault diagnosis, earthquake prediction, industrial design, natural language processing, automatic translation, decision support, decision analysis, multi-objective evaluation, and artificial intelligence.

FLT is used to obtain multiple attributes for quantitative analysis of semantics and images, as the logic of its functions is appropriate for inaccurate, unclear, and vague information. The fuzzy inference of FLT quantifies such information for analysis. However, a model of FLT only produces the overall values of various evaluation factors and does not allow calculation of a weight value and an order of the importance of each factor. Along with this, as the process of building a model is complicated, it is difficult to use commercial software and previous models to make a new model. This is because fuzzy sets, quantitative interval values, membership functions, and inference rules have unique characteristics in each model. In addition to this, procedures at each stage need to be newly created in each model, which needs different research for each model.

Research works that used FLT include 'identification and location of a transitional zone between an urban and a rural area' [40], 'analysis of operating performance using an integrated Bayesian network [41], 'improving performance and robustness [42], 'opinion mining' [43], 'analysis of the risk influencing factors in oil and gas pipeline projects' [44], 'classification of stakeholders of sustainable energy development in Iceland' [45], 'energy policy making', and 'applications of cultural and creative product design'.

3.4. Combining AHP and FLT

AHP and FLT have complementary functions to each other based on their strengths and weaknesses. When the quantitative evaluation of multiple attributes of a model requires overall quantitative output, relative weights, and a ranking of evaluation factors, the two methods can be used together. An AHP-FLT model takes into account the different influences of each evaluation factor in quantitative analysis. However, it is worth noting that combining two methods may be time-consuming as there is no repeated process in each method. In this research, we used the Delphi method to create a questionnaire for defining dimensions and factors. AHP and FLT were used together to find out which dimensions and factors are quantitatively significant.

4. Research Design

By considering the cons and pros of the Delphi method, AHP, and FLT, we combined these methods to establish a decision-making model for eco-friendly residence design. The overall research design is explained as follows. The flowchart of the Delphi questionnaire survey is shown in Figure 1. The Delphi questionnaire survey process includes (1) confirmation of research topics, (2) inviting experts, (3) preliminary evaluation of factors, (4) design and distribution of a Delphi questionnaire, and (5) questionnaire recovery. If the experts do not reach a consensus for the Delphi questionnaire, (4) and (5) are repeated to obtain the agreed evaluation factor. In this research, we had the questionnaire refined three times to obtain the experts' consensus. The experts who engaged in the discussion for the Delphi questionnaire did not participate in the questionnaire survey.

The Delphi expert questionnaire method is often confused with the expert field research method. Differences between the two are listed in Table 1. The Delphi method is an investigative method conducted using anonymous feedback. The process consists of acquiring expert opinions regarding all expected problems. The expert opinions are compiled and inducted, and the questionnaire is revised. Subsequently, experts receive anonymous feedback from other experts regarding their responses. The revised questionnaire is then returned to experts to acquire their opinions once again. The process is repeated until the expert responses reach a consensus [45]. The following is a detailed explanation of the Delphi method, AHP, and FLT. The same method has been applied to landscape design learning with a significant result [46].

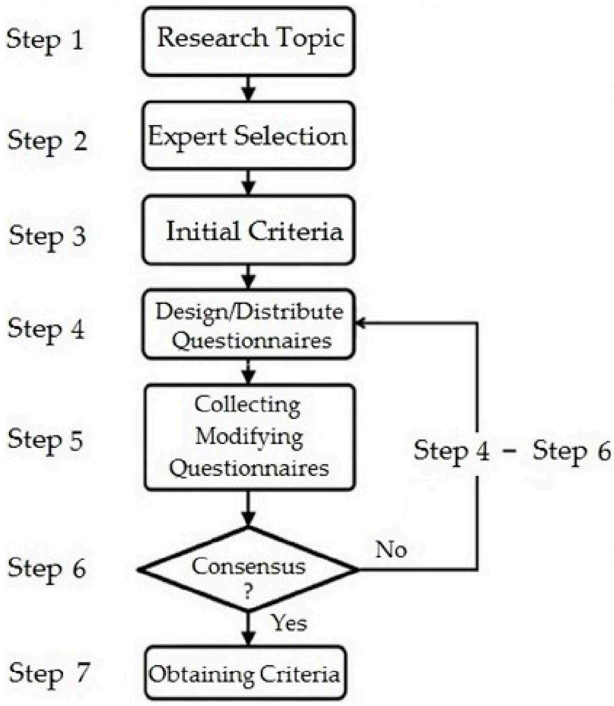

Figure 1. Flow chart for creating a questionnaire using the Delphi method.

Table 1. Comparison of Delphi method and Field research survey.

Items	Delphi Method	Field Research Survey
Subjective	Experts in industry, academia, and government	No specification
Interview method	Experts do not know each other for anonymity	No specification
Basis for decision	Consistency	Descriptive statistics
Purpose	Qualitative analysis to obtain conclusions and knowledge	Qualitative analysis

4.1. Delphi Method

Including five architects, two interior designers, two landscape architects, three CEOs of construction companies, and three architecture professors, a total of 15 experts were invited. They are professionals with more than 15 years of practical experience in residential design and the construction and repair of buildings. We used the following factors influencing the design of smart and green residential buildings proposed by Liu et al. as they had conducted a preliminary study before this research: sustainable development of a community, policy subsidies, environmental education, residents' participation, low-carbon life, ecological life, vegetation, sustainable living, sustainable lifestyle, consumers' social responsibilities and behavior, ecological restoration and biodiversity, ecological service function, and land resources planning [25]. We surveyed the invited experts with a questionnaire to define the preliminary impact factors for the Delphi questionnaire and iterated the survey process three times to obtain the final result. The survey result showed the factors to be considered for the low-carbon and eco-friendly residential design, with nine factors in three dimensions as follows.

- Green facilities: green building materials, photovoltaic power generation, energy-saving equipment
- Ecological facilities: green roof, planting/vegetation, rainwater collection/water recycling
- Community's participation: subsidies, resident participation, appropriate norms

The factors are referred to in AHP to establish a hierarchical structure and questionnaires with the concept of pairwise comparison.

4.2. AHP

A model with AHP was established based on the nine factors in the three dimensions as shown in Figure 2. Then, a questionnaire was created with the model and distributed to 85 respondents including residents, managers of residential buildings, architects, interior designers, landscape designers, construction managers, and professors teaching architecture. 62 valid questionnaires were recovered with a return rate of 72.9%. The survey result was coded in Microsoft Excel.

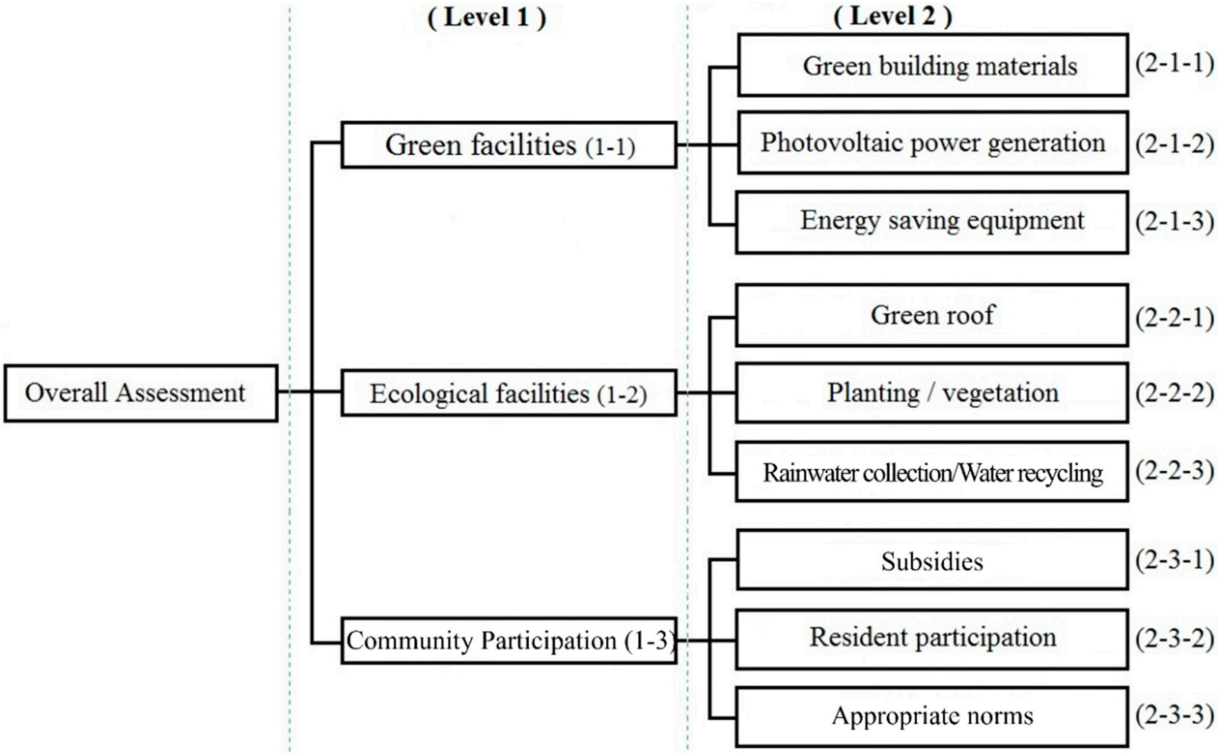

Figure 2. AHP hierarchy diagram in this study.

The questionnaire survey result needs to satisfy the consistency index (CI) ≤ 0.1 and consistency ratio (CR) ≤ 0.1. The random index (RI = CI/CR) depends on the number of factors in each dimension. A constant RI of 0.58 was obtained from the survey result. The relative weights of the factors in the dimensions at different levels are shown in Tables 2–5. The relative weights (w_i) of the factors are summarized in Table 6.

Table 2. Pairwise comparison of relative weights of three dimensions at level 1.

Dimension	Green Facilities	Ecological Facilities	Community Participation
Green facilities	1	2	0.89
Ecological facilities	0.5	1	1
Community participation	1.125	1	1
Weight	0.40	0.26	0.34
Remark	CI = 0.0357, CR = 0.0615, RI = 0.58		

Table 3. Pairwise comparison of relative weights of factors at level 2-1.

Pairwise Comparison	Green Building Materials	Photovoltaic Power Generation	Energy-Saving Equipment
Green building materials	1	0.80	0.89
Photovoltaic power generation	1.25	1	1.2
Energy-saving equipment	1.125	0.83	1
Weight	0.30	0.38	0.32
Remark	CI = 0.0002, CR = 0.0004, RI = 0.58		

Table 4. Pairwise comparison of relative weights of factors at level 2-2.

Pairwise Comparison	Green Roof	Planting/Vegetation	Rainwater Collection/ Water Reuse
Green roof	1	0.4	0.5
Planting/vegetation	2.5	1	2
Rainwater collection/ Water recycling	2	0.5	1
Weighting value	0.18	0.52	0.30
Remark	CI = 0.0212, CR = 0.0123, RI = 0.58		

Table 5. Pairwise comparison of relative weights of factors at level 2-3.

Pairwise Comparison	Subsidies	Resident Participation	Appropriate Norms
Subsidies	1	0.33	0.6
Resident participation	3	1	1.2
Appropriate norms	1.67	0.83	1
Weights	0.19	0.47	0.35
Remark	CI = 0.0122, CR = 0.0071, RI = 0.58		

Table 6. Relative weights (w_i) of factors in this study.

Level 1 (w_{i-1})	Level 2 (w_{i-2})	w_i	Ranking
Green facilities (1-1) (0.40)	Green building materials (2-1-1) (0.30)	0.120	5
	Photovoltaic power generation (2-1-2) (0.38)	0.152	2
	Energy-saving equipment (2-1-3) (0.32)	0.128	4
Ecological facilities (1-2) (0.26)	Green roof (2-2-1) (0.18)	0.047	9
	Planting/vegetation (2-2-2) (0.52)	0.135	3
	Rainwater collection/water recycling (2-2-3) (0.30)	0.078	7

Table 6. *Cont.*

Level 1 (w_{i-1})	**Level 2 (w_{i-2})**	w_i	**Ranking**
Community participation (1-3) (0.34)	Subsidies (2-3-1) (0.19)	0.065	8
	Resident participation (2-3-2) (0.47)	0.160	1
	Appropriate norms (2-3-3) (0.35)	0.119	6
The total weight (w_i)		1.00	
Remark	$w_i = w_{i-1} \times w_{i-2}$		

4.3. FLT

After defining the factors and calculating their relative weights, FLT is applied to establish the fuzzy logic inference system (FLIS) for the model. The FLIS has the function of quantitative inference. The purpose of using FLT is to establish FLIS that includes the fuzzy set, IF-THEN rule, membership function, and fuzzy range. FLIS processes complex issues with multiple factors that have different units and information such as ambiguous semantic information. FLIS converts complex inputs into easy ones for better interpretation.

A Delphi process is used to define parameters such as fuzzy set, fuzzy range, membership function, IF-THEN rule, and output. The definition of the parameter in this study is as follows.

- Fuzzy set

The fuzzy set is defined in each dimension of green facilities, ecological facilities, and community participation. The fuzzy set of green facilities includes five elements such as 'very good', 'good', 'average', 'not good', 'very bad' or 'very good', 'good', 'average', 'poor', and 'very poor'. The fuzzy set of ecological facilities and community participation has three elements such as 'good', 'general', 'bad' or 'high', 'medium', and 'low'. Thus, it is possible to have 45 fuzzy ($5 \times 3 \times 3 = 45$) for quantification by using FLT.

- Membership function (MF)

FLT is used to describe the degree of contribution of the factors to a model. In FLIS, the quantitative transfer is performed through logical deduction. The commonly used membership functions include Gauss–MF and Tri–MF.

- IF-THEN rule

IF-THEN rule is the center of FLIS inference, as the rule allows calculation and inference in FLIS in the same 2ay as that of the human brain.

- Fuzzy range

The fuzzy range means an interval range of the elements of a fuzzy set. Commonly used intervals are 0–100, 0–10, and 0–1. The range varies in different models. Defining the range is only for convenience, and the range does not affect the inference of FLIS.

After defining the parameters, the quantitative inference is carried out in FLIS. The inference has the following steps: input evaluation, input combination, fuzzifying, inference with an engine, defuzzifying, and quantifying and output values with IF-Then rule base. The schematic diagram of the inference in FLIS calculus is shown in Figure 3.

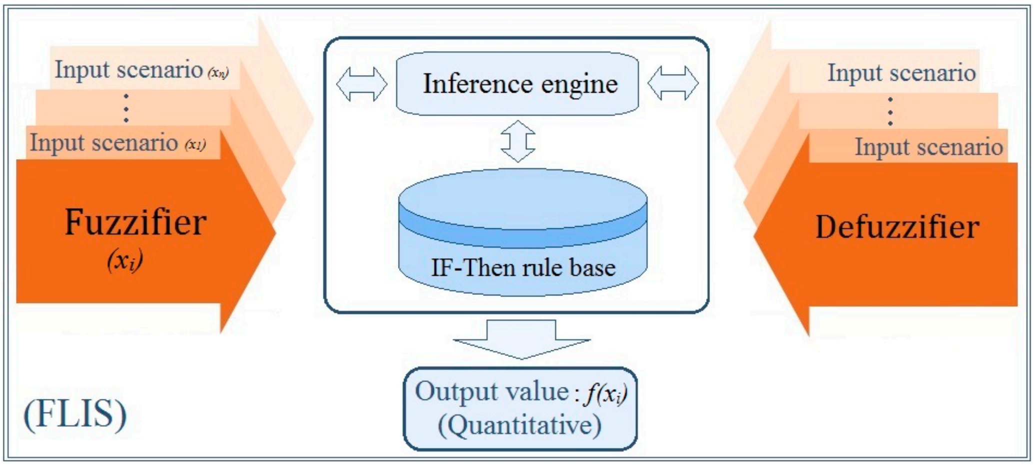

Figure 3. Schematic diagram of inference in FLIS.

There are 45 different input scenarios (x_i), and the corresponding output value is presented as $f(x_i)$. The fuzzy set and the fuzzy range are established by MATLAB. The output values of the parameters are shown in Table 7.

Table 7. Definition of parameters in FLIS with MATLAB.

Dimension	Fuzzy Sets	Fuzzy Range	Output Value
Green facilities	Very Good	0–100	0–100 Very good $\geq$ 85 84 $\geq$ Good $\geq$ 70 69 $\geq$ Average $\geq$ 55 54 $\geq$ Bad $\geq$ 40 Very bad $\leq$ 39
	Good		
	Average		
	Poor		
	Very Poor		
Ecological facilities	Good	0–100	
	Average		
	Poor		
Community participation	Great	0–100	
	Average		
	Bad		

Figure 3 shows that the FLIS established by applying fuzzy logic theory has completed the parameter definition of Table 6. FLIS has the function of quantitative decision analysis. The above parameters and inference rules cannot be automatically generated by commercial software, programming and case studies. The research focus of fuzzy logic theory is to complete the establishment of FLIS, which also includes the construction of the IF-THEN rule base, membership function operations, fuzzy operations, and other procedures. FLIS can handle complex issues with multiple attributes and can accept different input units and information. Different attributes or ambiguous semantic information, etc., different units, and imprecise semantic calculus are calculations that cannot be completed by traditional mathematical models, and FLIS can convert complex input information into information that is easy to apply and interpret

As there are 45 different scenarios in the dimensions of green facilities, ecological facilities, and community participation, the relations between the dimensions need to be presented in a three-dimensional diagram as shown in Figure 4. All the dimensions have output values, which implies that the low-carbon and eco-friendly residential design is appropriate for the development of a community.

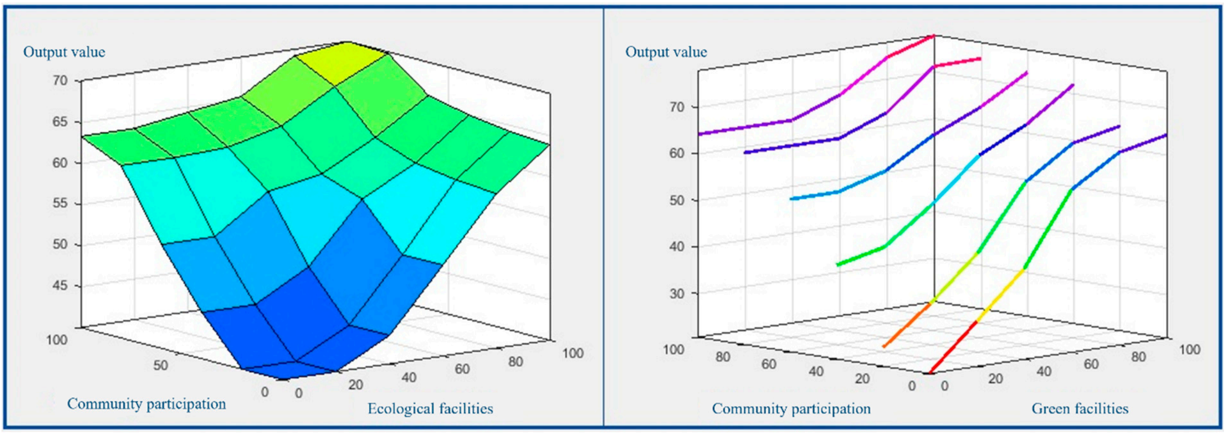

Figure 4. 3D relationship diagram of output values of each dimension.

5. Delphi-AHP-FLT Model

The Delphi-AHP-FLT (DAFuzzy) model has a complex modeling procedure as it needs to combine three methodologies altogether. The DAFuzzy model for the low-carbon and eco-friendly design is shown in Figure 5. It is presented that the hierarchical structure of AHP and FLIS is based on the Delphi process. AHP in the DAFuzzy model confirms the relative weight (w_i) of each factor, while FLIS calculates the output value $f(x_i)$ of each scenario. The final output value of the DAFuzzy model is expressed as $\sum(w_i) \times f(x_i)$ and is easy to compare and helpful for decision analysis.

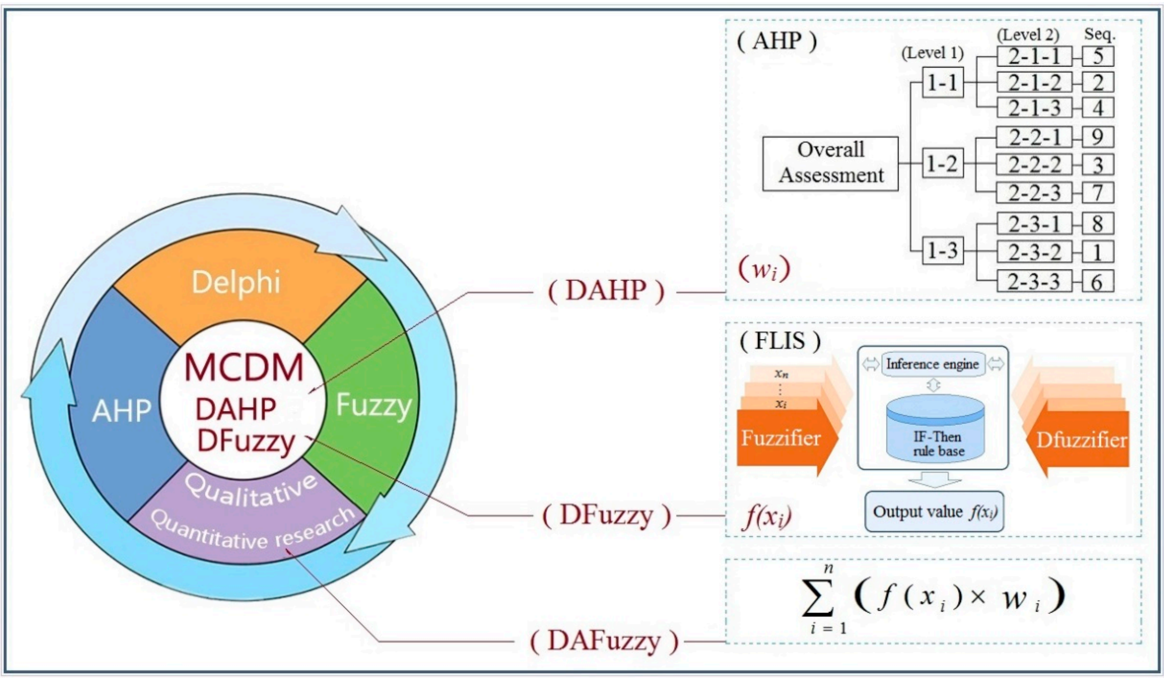

Figure 5. Architecture of DAFuzzy model.

Table 8 shows the best, general, and worst output values of the proposed DAFuzzy model among 45 different scenarios. The best scenario scores 89.8, the general scenario scores 57.5, and the worst scenario scores 18.7. The score for each factor is shown in Table 9, showing the impact degree of each factor.

Table 8. Output values of best, average, and worst cases of each dimension in the DAFuzzy model.

Dimension	Best Scenario	General Scenario	Worst Scenario
Green facilities	Very Good	Common	Very Poor
Ecological facilities	Very Good	Common	Poor
Community participation	Great	Common	Bad
Output value $f(x_i)$	89.8	57.5	18.7

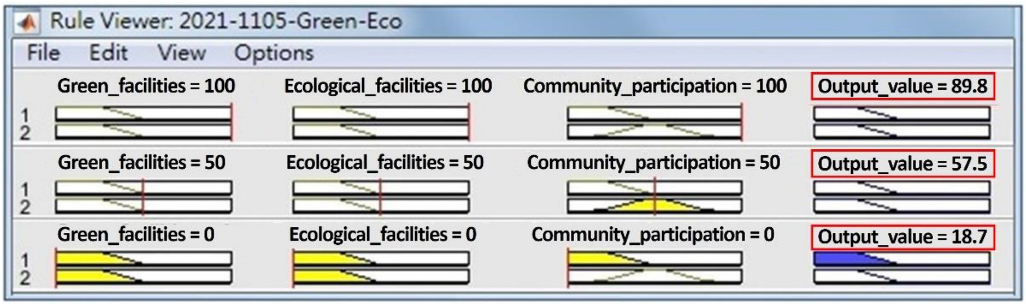

Table 9. Output values of best, average, and worst cases of each factor in the DAFuzzy model.

Factor	w_i	Best Scenario	General Scenario	Worst Scenario
		$f(x_i)$ = 89.8	$f(x_i)$ = 57.5	$f(x_i)$ = 18.7
		$w_i \times f(x_i)$	$w_i \times f(x_i)$	$w_i \times f(x_i)$
Green building materials	0.120	10.776	6.900	2.244
Photovoltaic power generation	0.152	13.649	8.740	2.842
Energy saving equipment	0.128	11.494	7.360	2.393
Green roof	0.047	4.220	2.702	0.878
Planting/vegetation	0.135	12.123	7.762	2.524
Rainwater collection/water recycling	0.078	7.004	4.485	1.458
Subsidies	0.065	5.837	3.737	1.215
Resident participation	0.160	14.368	9.200	2.992
Appropriate norms	0.119	10.686	6.842	2.225
Remark	Output value = $\sum (w_i) \times f(x_i)$			

6. Validation of the DAFuzzy Model

The DAFuzzy model is used to validate single or multiple cases by the qualitative forecasts in the Delphi method through AHP and FLT. The DAFuzzy model repor5ss the pros and cons of cases at the same time through inference and calculation via an Al process. Various inputs correspond to quantified output values with a high degree of objectivity. In brief, 45 scenarios (5 × 3 × 3) are used as input, and nine factors are found. The total number of combinations is 729 (9 × 9 × 9) for quantitative decision-making.

The proposed DAFuzzy model is validated by using two residential houses in Wenquan Town, Conghua District, Guangzhou city. The two houses were constructed based on low carbon-ecological space utilization and design. Therefore, a DAFuzzy model is required to analyze and evaluate how such concepts have been reflected in the houses. The result is expected to provide auxiliary decision-making before design and reconstruction.

Overview of Houses

Conghua district where the residential house is located is in an ecological town in the rich rural area in China's Pearl River Delta Economic Development Zone. Conghua district has been built with the support and guidance of the provincial authority. The house is the permanent venue of the International Eco-Design Conference. It was designed as an eco-friendly renovated residential building. There are large and luxurious residential houses and mansions near the house in the community. The 3D simulated pictures of the houses are shown in Figure 6 and the floor plan of the house is presented in Figure 7.

(**a**) (**b**)

Figure 6. 3D simulated pictures of the residential houses for validation of the DAFuzzy model in this study. (**a**) House 1, (**b**) House 2.

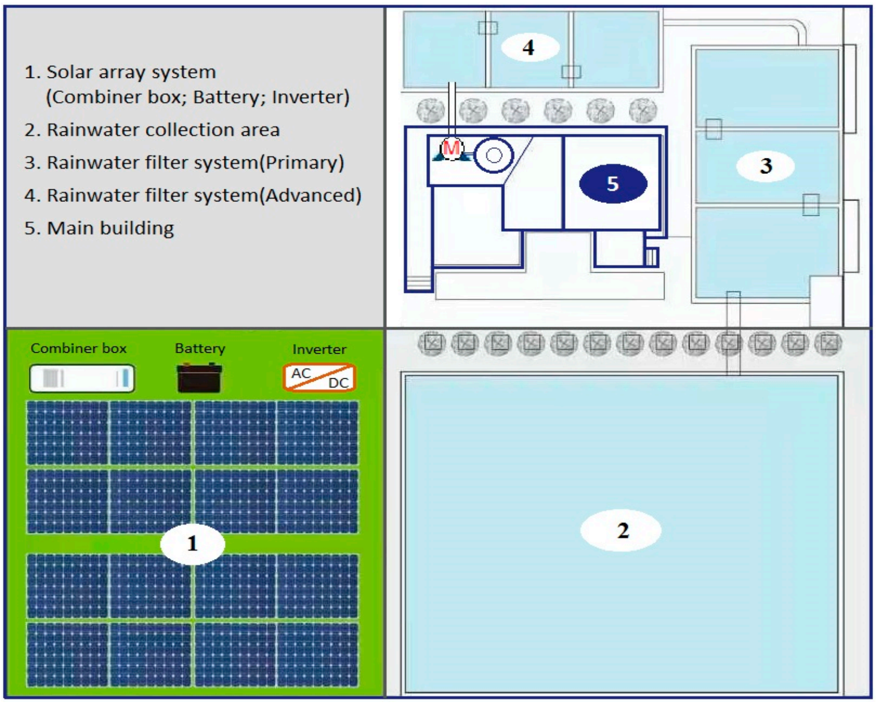

Figure 7. Green and ecological facilities of the residential house.

We applied the proposed DAFuzzy model to the residential house for validation of the model. The result is described in Tables 10 and 11. Case 1 has higher scores than 85 for each dimension and its output value is 80.2, while case 2 shows a score of 50–70 with an output value of 62.6. The scores of the factors show that photovoltaic power generation, energy-saving equipment, planting/vegetation, and resident participation are important for the low-carbon and eco-friendly residential house design with higher output values than other factors.

Table 10. Output values of each dimension of the residential houses (cases 1 and 2) from the DAFuzzy model.

Dimension	Case 1	Case 2
Green facilities	90 (very good)	60 (general)
Ecological facilities	85	70
Community participation	85	50
Output value $f(x_i)$	80.2	62.6

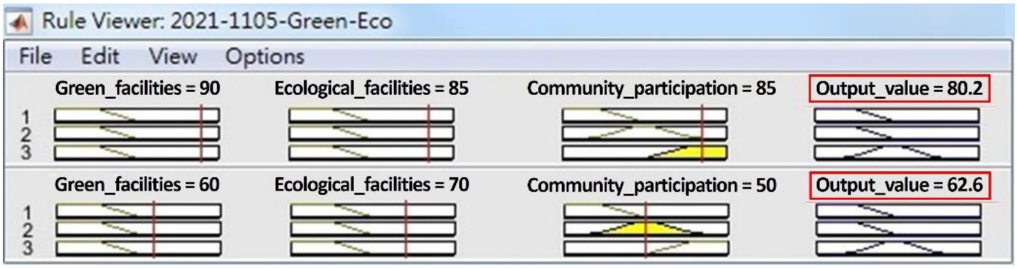

Table 11. Output values of each factor of the residential houses (cases 1 and 2) from the DAFuzzy model.

Factor	w_i	Case 1	Case 2
		$f(x_i)$ = 80.2	$f(x_i)$ = 62.6
		$w_i \times f(x_i)$	$w_i \times f(x_i)$
Green building materials	0.120	9.624	7.512
Photovoltaic power generation	0.152	12.190	9.515
Energy-saving equipment	0.128	10.265	8.012
Green roof	0.047	3.769	2.942
Planting/vegetation	0.135	10.827	8.451
Rainwater collection/water recycling	0.078	6.255	4.882
Subsidies	0.065	5.213	4.069
Resident participation	0.160	12.832	10.016
Appropriate norms	0.119	9.534	7.449
$\sum = w_i \times f(x_i)$		80.509	62.848

7. Discussions and Conclusions

First, we define factors and dimensions by using the Delphi method and surveying experts in the related fields of academia and industry. Three dimensions of green facilities, ecological facilities, and community participation are selected along with the following nine factors: green building materials, photovoltaic power generation, energy-saving equipment (green facilities), green roof, planting/vegetation, rainwater collection/water recycling (ecological facilities), subsidies, resident participation, and appropriate norms (community participation). Then, AHP and FLT are applied to obtain the relative weights for the importance of the factors and the dimensions, which are used for calculating the output values.

The relative weight of each dimension is 0.4 for green facilities, 0.34 for community participation, and 0.26 for ecological facilities. The highest weight of green facilities is contributed to by subsidies from the government for installing energy-saving equipment. The reason for the low impact of ecological facilities is that rainwater collection and planting/vegetation require a large open space, and this is equally is considered for the eco-friendly design of the residential house. In total, 45 different scenarios are evaluated for the proposed DAFuzzy model. The best scenario scores 89.8, the general scenario scores 57.5, and the worst scenario scores 18.7. In the best scenario, green facilities and ecological facilities are more important than community participation. The factors that are important in the best scenario are resident participation, photovoltaic power generation, planting/vegetation, energy-saving equipment, green building materials, appropriate norms, rainwater collection/water recycling, subsidies, and green roof, in order of output value.

The proposed model is validated with two residential houses in Conghua District, Guangzhou city, China. The previous research has proven the validity of the DAFuzzy model in product design, energy system development [14], and education in land design [46]. Thus, we apply the model in the design of an eco-friendly house. In the model, the output values show that the influencing factors are resident participation, photovoltaic power generation, planting/vegetation, energy-saving equipment, green building materials, appropriate norms, rainwater collection/water recycling, subsidies, and green roof, in order of output value. In addition to this, the case 1 house is closer to the best scenario than the case 2 house.

Increasing environmental pollution and intensifying climate change caused by increasing CO_2 emissions are regarded as serious problems. Thus, it has become important to promote a low-carbon and eco-friendly method of construction. Thus, eco-friendly residential houses are necessary for society to develop, considering people, culture, green, land, scenery, and production. Thus, we propose a decision-making model with factors that are needed for the building of eco-friendly residential houses. To establish an appropriate model, we combine the Delphi method, AHP, and FLT to define the appropriate factors and dimensions and discover important attributes for designing and constructing eco-friendly residential houses. After establishing a model, we validated it by applying the model to two residential houses in Conghua District, Guangzhou city, China.

The research result with the proposed DAFuzzy model in this study implies that promoting the development of a low-carbon and eco-friendly environment requires new policies and a large investment. The result of the validation of the model shows that building a low-carbon and eco-friendly house needs the support of the government and people's understanding of the importance of an eco-friendly environment and enthusiasm for participation. The proposed model in this study provides the understanding of factors to be considered for the eco-friendly design of the residential house and the basis for making policies and decisions to pursue a low-carbon and eco-friendly society. The result for low-carbon and eco-friendly houses can be a reference for decision-making on the sustainable design of smart low-carbon cities in the future.

Author Contributions: Writing and reviewing, S.-L.H.; data collection, Y.S.; data analysis, Y.Z. and N.X.; English editing and reviewing the manuscript, T.-H.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

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

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