Research on the Development Path of Green Buildings based on the Integrated Model of Structural Equation and System Dynamics

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Abstract

Driven by China's "dual carbon" goals, the green transformation of the construction industry has become a crucial path to achieve low-carbon development. This study focuses on the development of green buildings in Shandong Province. By applying and integrating the Structural Equation Model (SEM), FP-growth association rule mining, and the system dynamics model, it systematically analyzes the residents' cognitive differences regarding green buildings, the influencing factors of their willingness to accept, and the promotion paths of enterprises.The study reveals that there are group differences in residents' cognition of green buildings. Those aged 18-35, with high incomes, and self-employed individuals have a higher level of awareness, while the acceptance level of those over 55 years old and low-income groups is relatively low. The acceptance attitude, trust in the government, and recognition from relatives and friends significantly influence the purchase intention. The public pays attention to logistics support, comfort, and health, and there is a need to optimize policy subsidies.The system dynamics simulation shows that by 2035, the ecological and economic benefits of green buildings in Shandong Province will reach 1.311 billion yuan and 2.184 billion yuan respectively. This study provides ideas for the promotion of green buildings in Shandong Province and has reference significance for facilitating the low-carbon transformation of the industry.

Keywords

Green Buildings, Structural Equation Model, FP-Growth Association, System Dynamics Model.

1. Introduction

Against the backdrop of global climate change and the "dual carbon" goals, the construction industry, as a key area of energy consumption and carbon emissions, its green transformation has become an important path to achieve sustainable development. Green buildings, through comprehensive technical means such as energy conservation, water conservation, material conservation, and optimization of the indoor environment, significantly reduce the environmental impact throughout the building's life cycle, and have become the focus of policies and academic research in various countries[1].

In recent years, China has made remarkable progress in the field of green buildings. As a major province in terms of population and economy, Shandong Province has actively responded to national policies. During the "14th Five-Year Plan" period, the newly added scale of green buildings in Shandong Province ranks among the top in the country, and it has promoted practices such as prefabricated buildings and zero-carbon communities, providing important support for regional low-carbon development. However, despite the continuous progress at the policy and technical levels, the popularization of green buildings still faces multiple challenges[2].

Existing studies have shown that there are significant group differences in residents' cognition of green buildings, and their willingness to accept is complexly influenced by economic, social, and policy factors. Enterprises, on the other hand, face promotion bottlenecks such as high costs and insufficient market awareness. In addition, there is a lack of research on the technical adaptability to regional climate characteristics, and the absence of systematic benefit evaluation and optimization of promotion strategies restricts the large-scale development of green buildings[3].

Currently, research on green buildings mostly focuses on technical performance or policy analysis, and there are few multi-dimensional integrated discussions that combine residents' cognition, corporate behavior, and regional characteristics. In particular, there is a lack of empirical research on Shandong Province, a typical region. Moreover, existing literature has methodological limitations in quantifying the ecological and economic synergistic benefits of green buildings, and fails to fully reveal the dynamic interaction mechanism among policies, technologies, and the market[4].

Taking Shandong Province as a case, this study comprehensively applies methods such as the structural equation model and system dynamics simulation to systematically analyze the key influencing factors of residents' cognition and willingness to accept, explore the pain points and needs of enterprise promotion, and construct a technical evaluation model based on the geographical and climatic characteristics of Shandong Province. It screens suitable technologies and calculates their carbon reduction benefits. By dynamically simulating and predicting the medium- and long-term ecological and economic values of green buildings, this study aims to provide a scientific basis for the government to formulate differentiated policies and for enterprises to optimize their market strategies. At the same time, it provides a reference for the promotion of green buildings in other regions, and helps the construction industry achieve low-carbon transformation and the realization of the "dual carbon" goals.

2. Research Methods and Model Construction

2.1. Data Collection

This study focuses on the development of green buildings in Shandong Province. In order to have an in-depth understanding of the promotion status, residents' cognition, willingness to accept, and the promotion situation by enterprises, a multi-dimensional dataset has been constructed. Through the questionnaire survey method, 1,141 consumer questionnaires were collected in different cities of Shandong Province. After screening, 1,054 valid consumer questionnaires were obtained, with an effective questionnaire rate of 92.38%. To ensure the validity of the questionnaire data, the Cronbach's α coefficient was used to test the reliability of the questionnaire. The formula is as follows:

$$\alpha = \frac{k}{k-1}\left(1 - \sum_{i=1}^{k} \sigma_i^2/\sigma_T^2\right) \quad (1)$$

where k is the number of questions in the questionnaire, σ_i^2 is the variance of the score of the i -th question, and σ_T^2 is the variance of the total score of the questionnaire.

After calculation, the Cronbach's α coefficient of this questionnaire is 0.86 , indicating that the questionnaire has high reliability.

2.2. Structural Equation Model

Structural Equation Modeling (SEM) is a multivariate statistical method that combines factor analysis and path analysis[5]. It can effectively handle the complex relationships between multiple independent and dependent variables while taking measurement errors into account. In green building research, it is often used to explore the influencing factors of residents' willingness to accept green buildings and their interrelationships.

Its basic principle is to construct a relationship model between latent variables (concepts that cannot be directly measured, such as residents' acceptance attitudes towards green buildings, perceived norms, etc.) and observed variables (directly measurable indicators, such as evaluations of green building design functions, recommendation intentions, etc.). The structural equation model consists of two parts: the measurement model and the structural model.

The measurement model describes the relationship between latent variables and observed variables. The formulas are as follows:

$$\begin{aligned} X &= \Lambda_x \xi + \delta \\ Y &= \Lambda_y \eta + \epsilon \end{aligned} \tag{2}$$

Where X and Y are vectors of exogenous and endogenous observed variables, respectively; ξ and η are vectors of exogenous and endogenous latent variables, respectively; Λ_x and Λ_y are the corresponding factor loading matrices, reflecting the influence degree of latent variables on observed variables; δ and ϵ are vectors of measurement errors.

The structural model depicts the causal relationships between latent variables. The formula is:

$$\eta = B\eta + \Gamma\xi + \zeta \tag{3}$$

Where B is the path coefficient matrix between endogenous latent variables, Γ is the path coefficient matrix of exogenous latent variables on endogenous latent variables, and ζ is the residual vector of the structural equation.

In the research on residents' willingness to accept green buildings, latent variables such as acceptance attitude, perceived norm, subjective norm, and government trust are used. The data of observed variables are obtained through surveys, and the structural equation model is used to analyze the mutual influence paths and degrees among these latent variables.

2.3. Association Rule Mining

Association rule mining aims to discover interesting association relationships between item sets from a large amount of data[6]. In green building research, it can be used to analyze the internal relationships between residents' willingness to promote green buildings and various influencing factors.

Its core concepts include Support, Confidence, and Lift. Support measures the frequency of a rule's appearanc in the dataset. The formula is:

$$\text{Support}(X \Rightarrow Y) = \frac{\sigma(X \cup Y)}{N} \tag{4}$$

Where X and Y are item sets, σ(X ∪ Y) represents the number of transactions containing X and Y, and is the total number of transactions.

Confidence evaluates the probability that Y is also included in the transactions containing X. The formula is:

$$\text{Confidence}(X \Rightarrow Y) = \frac{\sigma(X \cup Y)}{\sigma(X)} \tag{5}$$

Lift is used to judge the practicality of a rule and measure the impact of the appearance of X on the appearance of Y. The formula is:

$$\text{Lift}(X \Rightarrow Y) = \frac{\text{Confidence}(X \Rightarrow Y)}{\text{Support}(Y)} \tag{6}$$

In the analysis of the influencing factors of residents' willingness to promote green buildings, based on the sample answers to the question "After understanding and accepting green buildings, which of the following factors make you more willing to recommend them to others", algorithms such as FP - growth are used to mine association rules.

2.4. System Dynamics Model

System Dynamics (SD) is a method based on feedback control theory and is used to study the dynamic behavior of complex systems[7]. In the analysis of the development prospects of green buildings, by constructing a system dynamics model, it can simulate the changes in energy consumption, ecological benefits, and economic benefits of green buildings under the influence of different policies, technologies, and other factors, providing a decision - making basis for the formulation of green building development strategies.

The system dynamics model mainly consists of stocks, flows, auxiliary variables, and constants. Stocks are the accumulation amounts in the system, reflecting the state of the system at a certain moment; flows are used to describe the change rate of stocks; auxiliary variables are used to assist in model construction and calculation; and constants are fixed parameters.

Its basic principle is based on feedback loops. The variables in the system interact with each other to form positive and negative feedback loops. Positive feedback will enhance the system behavior, while negative feedback plays a role in regulating and stabilizing the system. In the modeling process, software such as Vensim is used to determine the system boundary, variable relationships, and parameters according to the research problem.

Taking the green building development model as an example, assuming conditions such as a stable economic and social situation and a stable growth of energy consumption, three subsystems of social economy, policy, and building energy consumption are determined. The time span of the model is from 2016 to 2035, and simulations are carried out by collecting data from 2016 to 2022. The system dynamics model is shown in Figure 1.

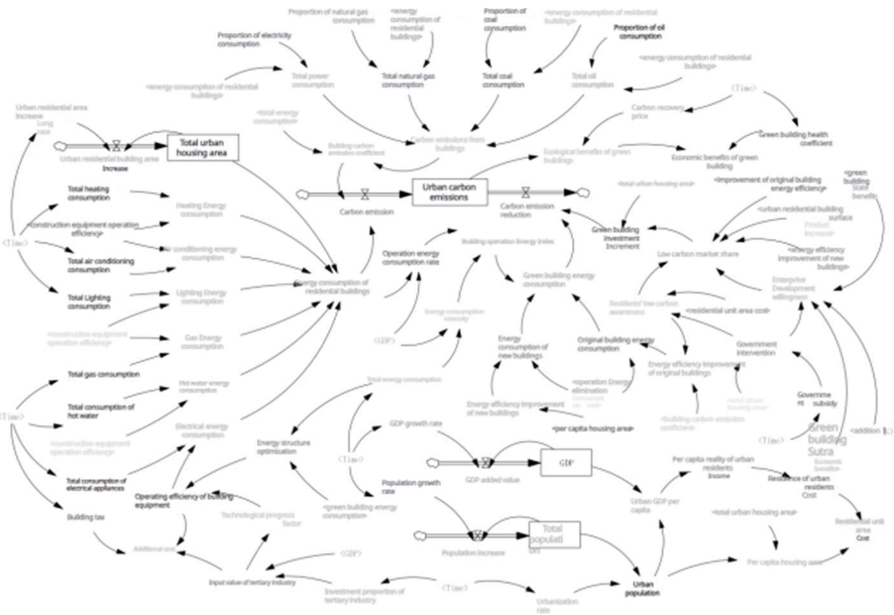

Figure 1. The System Dynamics Model Constructed in This Study

3. Results

Based on the structural equation, the mutual influences among latent variables are quantified. The results are shown in Figure 2, Table.1 and Table.2. The error variance of the model is positive, and indicators such as CFI, NFI, and NNFI are greater than 0.9, and the RMSEA value is 0.02, which indicates that the overall goodness-of-fit of the model is good and the research results have high credibility.

The study shows that the path coefficients among all latent variables are significant at the 95% confidence level, verifying the rationality of the hypothesis. The influence weight of the acceptance attitude on the residents' willingness to accept green buildings is the largest, and the indirect effect of the perceived norms through the acceptance attitude is the second. Among the observed variables, the design functions of green buildings have a significant impact on the acceptance attitude, but the residents' willingness to recommend needs to be improved. The residents recognize the value of green buildings and are willing to purchase them at a high price, but they lack the initiative to obtain information, and all factors play a role.

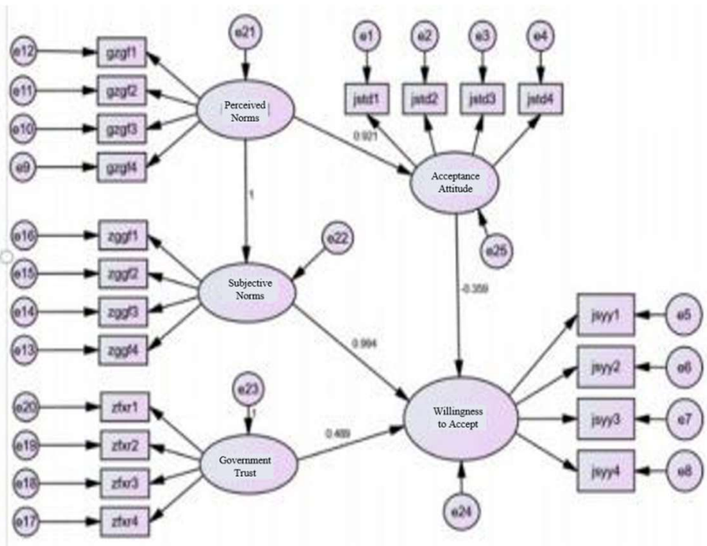

Figure 2. Path Analysis of the Structural Equation Model

Table 1. Goodness-of-Fit Test Table of the Structural Equation Model

P	GFI	RMSEA	RMR	CFI	NFI	NNFI
<0.05	>0.9	<0.10	<0.05	>0.9	>0.9	>0.9
0.000***	0.945	0.02	0.571	0.993	0.945	0.992

Table 2. Path Coefficient Table of the Structural Equation Model

Latent Variable	Manifest Variable	Standardized Coefficient	Standard Error	P
Perceived Norms	Acceptance Attitude	0.921	0.053	0.000***
Perceived Norms	Subjective Norms	0.869	0.049	0.000***
Acceptance Attitude	Willingness to Accept	0.812	0.046	0.000***
Subjective Norms	Willingness to Accept	0.623	0.042	0.000***
Government Trust	Willingness to Accept	0.489	0.036	0.000***

To deeply explore the internal relationships between residents' willingness to promote and five factors such as policy subsidies and logistics support, this study is based on the association rule analysis of FP-growth. Using the sample answers to the question "After understanding and accepting green buildings, which of the following factors make you more willing to recommend them to others?", it comprehensively analyzes the degree of association between the above factors and the willingness to promote, aiming to deeply analyze the influencing factors of consumers' willingness to promote green buildings.

Through systematic analysis, a total of 10 valid association rules have been mined, and the specific model estimation results are shown in the Table 3.

The association rule analysis shows that support is a key indicator for measuring the popularity of rules.The study concludes that: Logistics support and comfort and health have a "core strong association", and the two influence each other, which is the core concern of residents; Cost is a "multidimensional association link", which has a diverse impact on residents' willingness and decision-making to promote; Logistics support has "extensive radiation", and many factors form association rules around it. In addition, residents with different media preferences have different focuses: those who prefer traditional media pay attention to comfort and health, etc., while those who prefer online media value logistics support and pay attention to developers.

Table 3. Results of Association Rule Analysis

Antecedent	Consequent	Support	Confidence	Lift	Conviction
Logistics Support	Comfort and Health	0.406	0.612	0.01	0.962
Comfort and Health	Logistics Support	0.406	0.648	0.01	0.956
Policy Subsidies	Logistics Support	0.328	0.643	0.011	0.94
Aesthetic Design	Logistics Support	0.279	0.551	0.057	0.748
Cost	Comfort and Health	0.211	0.825	0.051	2.139
Cost	Logistics Support	0.143	0.558	0.027	0.76
Comfort and Health, Policy Subsidies	Logistics Support	0.14	0.573	0.022	0.788
Cost	Comfort and Health, Logistics Support	0.136	0.531	0.032	1.266
Cost, Logistics Support	Comfort and Health	0.136	0.951	0.046	7.614
Comfort and Health, Cost	Logistics Support	0.136	0.643	0.004	0.941

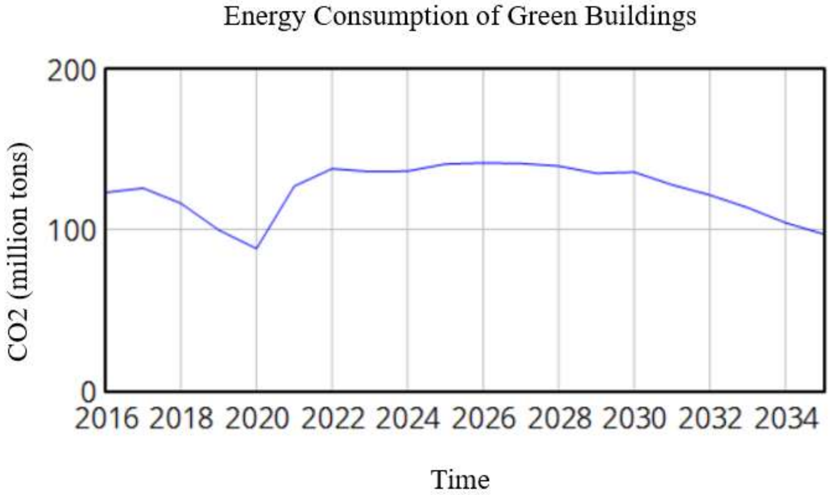

Figure 3. Simulation of Predicted Energy Consumption of Green Buildings

The system dynamics simulation is shown in Figure 3. Under the low-carbon policy, the energy consumption of green buildings accounts for 2.08% of the total building energy consumption and continues to decline, while the energy consumption of existing buildings first increases and then decreases; the energy consumption of green buildings continues to decline.

Since 2022, the ecological and economic benefits of green buildings in Shandong have been climbing. The ecological benefit was 297 million yuan in 2023 and is expected to reach 1.311 billion yuan in 2035; the economic benefit was 495 million yuan in 2023 and will reach 2.184 billion yuan in 2035, which is the result of the comprehensive effect of multiple factors such as policies and technologies.

4. Conclusion

Through a systematic analysis of the current development situation of green buildings in Shandong Province, this study reveals key issues such as residents' cognitive differences, enterprises' promotion dilemmas, and technical adaptability, and puts forward targeted development suggestions. The study finds that the high-income group aged 18-35 has a relatively high acceptance of green buildings, while the elderly and low-income groups have insufficient awareness. It is recommended that the government formulate differentiated publicity strategies for different groups of people. For example, it should strengthen the promotion through online media for the young group, and carry out community science popularization activities for the elderly group. In response to the problem of high costs faced by enterprises, it is recommended to increase the intensity of fiscal and tax subsidies, establish special research and development funds, and at the same time promote industry-university-research cooperation to reduce the cost of technology application. The study also suggests establishing a regional technical standard system for green buildings, focusing on promoting energy-saving technologies such as ground-source heat pumps that are suitable for the local climate characteristics, and enhancing market confidence through the construction of demonstration projects. In addition, the supervision mechanism should be improved to ensure the effective implementation of policies, regularly evaluate the energy conservation and emission reduction effects of green building projects, and provide data support for subsequent policy adjustments. The implementation of these measures will effectively promote the large-scale development of green buildings in Shandong Province and provide a replicable experience model for the low-carbon transformation of the construction industry across the country.

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