Journal of Education and Educational Research
ISSN: 2957-9465 | Vol. 10, No. 2, 2024

Research on the Impact of User Behavior on Sustainable Design Strategies

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Abstract: This study aims to explore the influence of user behavior on sustainable design strategies and proposes a framework for optimizing design interventions. User behavior data regarding energy use, resource consumption, and waste management were collected through surveys, in-depth interviews, and virtual reality simulations. K-means clustering and Principal Component Analysis (PCA) were employed to systematically identify user behavior patterns. The findings reveal three distinct user groups: environmentally conscious, economically driven, and neutral/passive. Experimental results validated the effectiveness of various design intervention strategies—such as behavioral incentives, interactive feedback, and visual prompts—in increasing the frequency of energy-saving actions and reducing energy consumption. The behavioral incentive strategy showed the most significant impact, reducing energy consumption by 20% and achieving the highest user satisfaction. Through multiple regression analysis and ANOVA, the statistical significance of the behavioral incentive strategy was further confirmed. The innovation of this study lies in optimizing user behavior through customized strategies and proposing a combination of interventions to achieve greater energy savings. This provides new theoretical and practical support for sustainable design practices.

Keywords: User Behavior; Sustainable Design; Behavioral Incentive Strategy; Energy Consumption; Design Intervention.

1. Introduction

With the acceleration of globalization, environmental issues are becoming increasingly severe, and resource consumption is intensifying. Sustainable development has emerged as a critical topic across various fields, particularly in design. Sustainable design aims to maximize ecological benefits by optimizing product lifecycles, reducing resource consumption, and minimizing environmental pollution. However, despite the widespread application of sustainable design strategies in both theory and practice, the influence of user behavior on these strategies has not been fully understood or addressed. In fact, users' daily actions, consumption habits, and resource utilization directly impact the effectiveness of design strategies. Therefore, studying the influence of user behavior on sustainable design strategies has become crucial to advancing sustainable design practices.

In recent years, the relationship between sustainable design and user behavior has garnered increasing attention in both academia and practice. As environmental issues worsen, sustainable design is seen as an essential means of mitigating resource depletion and environmental pollution. Sustainable design not only involves optimizing product lifecycles but also necessitates an understanding of users' behavior patterns in product usage, resource consumption, and waste management. Hence, how design can effectively guide users toward more environmentally friendly behaviors has become a core issue for scholars.

Energy-efficient building design is a typical area for studying the impact of user behavior on energy consumption. Research by Santin et al. revealed that user behavior plays a key role in building energy consumption. Even under the same building conditions, the energy consumption of different users' habits may vary by several multiples[1]. This finding was corroborated by Gram-Hanssen , who further demonstrated that optimizing user behavior can significantly improve building energy performance[2]. Additionally, Anderson and Newman examined user behavior in smart home systems and found that combining smart technology with user behavior can achieve higher energy efficiency[3]. Although these studies provide insights into how user behavior affects energy consumption in buildings, they largely focus on the building environment and overlook the influence of user behavior in other design fields.

In the field of product design, user behavior related to product use and disposal also significantly impacts the achievement of sustainability goals. Laitala and Boks pointed out that although many design strategies aim to extend product lifecycles, user behavior—such as maintenance and recycling habits—remains a crucial factor in determining the product's lifecycle[4]. They found that users' awareness and actions regarding material recycling greatly influence the effectiveness of design strategies. Further research by Cooper et al. suggested that promoting proactive user behavior through design, such as raising awareness of product repair and recycling, can significantly extend product lifecycles and reduce resource waste[5].From a social psychology and behavioral economics perspective, users' environmentally friendly behaviors are not only influenced by design strategies but also by their intrinsic motivations and social-cultural norms. Thøgersen indicated that even when design strategies offer more environmentally friendly products and services, users' choices are often influenced by psychological motivations and external social norms[6]. This influence was further validated by Verplanken et al., who demonstrated that behavioral interventions, such as providing instant feedback and economic incentives, can effectively change users' consumption behavior[7]. These findings suggest that a single design strategy may not be sufficient to achieve comprehensive sustainability goals. Instead, design should be combined with behavioral economics to develop integrated strategies that can alter user habits.

In response to these challenges, design intervention strategies have become a research focus. Lockton et al. proposed that design methods such as behavioral incentives, feedback systems, and visual prompts can effectively guide users toward energy-saving behaviors[8]. For example, Levine showed how introducing a dynamic feedback system allows users to understand the impact of their actions on energy consumption in real-time, thereby encouraging behavior change[9].Although previous studies have highlighted the importance of user behavior in sustainable design strategies, significant gaps remain in the current literature. First, most research has concentrated on either building or product design, lacking a cross-disciplinary framework to systematically analyze the interaction between user behavior and sustainable design. Second, the personalization and adaptability of design intervention strategies have not been adequately addressed. Due to the complexity of user behavior patterns, existing design interventions often struggle to optimize for specific user groups. This indicates the need for further exploration into customized design intervention strategies based on user behavior analysis to enhance their effectiveness in real-world applications.

Based on this literature review, this study aims to systematically investigate the impact of user behavior on sustainable design strategies through customized design interventions. Unlike previous studies, this research is not limited to building or product design but instead analyzes user behavior in energy use, resource consumption, and waste management from an interdisciplinary perspective. K-means clustering and Principal Component Analysis (PCA) were employed to systematically identify user behavior patterns, and experiments were conducted to validate the effectiveness of different design interventions, such as behavioral incentives, interactive feedback, and visual prompts. The research findings will provide theoretical support for future sustainable design practices and offer guidance for developing personalized design interventions.

2. Materials and Methods

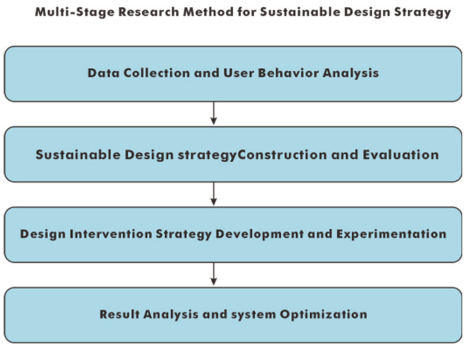

Figure 1. Multi-Stage Research Method for Sustainable Design Strategy

This experiment employed a multi-phase research approach to comprehensively explore the impact of user behavior on sustainable design strategies and develop a framework for optimizing design strategies. The research process was divided into four main stages: data collection and user behavior analysis, the construction and evaluation of sustainable design strategies, the development and experimental validation of design intervention strategies, and results analysis and system optimization (see Figure 1). Each stage integrated both quantitative and qualitative methods to ensure the comprehensiveness of the research and the reliability of the results.

2.1. Data Collection

To ensure the breadth and representativeness of the research data, this study collected data on the relationship between user behavior and sustainable design strategies through questionnaires, in-depth interviews, and virtual reality simulation experiments.

The data collection in this study consists of two parts: the first part involves user behavior data obtained through questionnaires and in-depth interviews, while the second part comprises sustainable design-related data extracted from existing literature and case studies. The questionnaires were primarily targeted at specific user groups (e.g., household users, office workers) and covered their behavioral patterns in energy use, resource consumption, waste management, and product usage habits. In-depth interviews aimed to delve into users' behavioral motivations, attitudes, and factors influencing potential behavioral changes. To ensure data representativeness, users from various regions, covering different ages, genders, occupations, and socio-economic backgrounds, were selected for the surveys and interviews. Literature data were primarily sourced from existing sustainable design research and case analyses, focusing on the relationship between user behavior and design strategies as reported in prior studies.

2.1.1. Questionnaire Design

This study designed a questionnaire focused on behaviors related to energy use, resource consumption, and waste management, aiming to gather actual behavioral data from users' daily lives. The questionnaire was based on a Likert scale and covered multiple dimensions such as energy use habits, energy-saving awareness, and recycling habits. It was distributed through an online platform, with a sample population including users of different genders, ages, occupations, and educational levels to ensure the diversity and generality of the data.

2.1.2. In-depth User Interviews

A total of 30 users were interviewed in this study, with an average age of 35, spanning different age groups from 20 to 60 years old to ensure data diversity and representativeness. Of the interviewees, 53% were male, and 47% were female, with professional backgrounds ranging from professionals, educators, technicians, and service industry workers to freelancers. Regarding educational levels, 73% of the respondents held a bachelor's degree or higher, while 27% had a high school or vocational diploma. All interviews were conducted in a quiet and undisturbed environment, with respondents informed in advance that their data would remain strictly confidential, and their consent for audio recording was obtained. During the interviews, the researcher acted as a facilitator, avoiding excessive intervention and encouraging respondents to express their opinions freely. After each interview, the researcher immediately organized and analyzed the content to ensure accuracy and completeness of the information.

2.1.3. Literature Extraction of Relevant Data

To support and validate the user behavior analysis, this study extracted both quantitative and qualitative data related to sustainable design from existing literature and real-world case studies. These data include cases of successfully implemented sustainable design strategies, covering product and service designs in various fields such as home appliances, building materials, and packaging design. The cases provide detailed information on design strategies, implementation methods, and final outcomes, and they analyze the relationship between design strategies and user behavior to identify success factors and areas for potential improvement. Additionally, this study extracted commonly used sustainable design evaluation metrics, such as environmental impact (e.g., carbon footprint, energy consumption, water resource usage), economic benefits (e.g., cost-effectiveness, product lifespan), and social impact (e.g., user satisfaction, behavioral change). These metrics serve as reference standards for evaluating design strategies. The literature also highlights the influence of user behavior on the success of design strategies, particularly in terms of environmental awareness, behavioral engagement, cultural background, social norms, and psychological factors. These studies provide theoretical support for the user behavior analysis in this research. Lastly, effective design interventions, such as visual prompts, interactive design, and incentive mechanisms, were extracted from specific design cases and will be further applied and validated in the development of design strategies in this study.

2.2. Data Preprocessing

2.2.1. Data Collection and Validity

A total of 500 valid questionnaires and 50 in-depth interview records were obtained in this study. These data cover users from different regions, ages, genders, occupations, and socio-economic backgrounds, ensuring the diversity and representativeness of the sample. After an initial screening of the questionnaire and interview data, it was confirmed that all 500 questionnaires and 50 interviews were complete and consistent, thus regarded as valid data.

2.2.2. Data Cleaning

During the data cleaning process, the research team followed several key steps. First, for approximately 5% of the 500 questionnaires with missing values, the mean imputation method was used for numerical data, and the mode imputation method was applied for categorical data to maintain the completeness of the dataset. Second, outliers were detected using box plots and the Z-score method, and extreme values in energy consumption were adjusted using the Winsorization method, which modified them to more reasonable boundary values, reducing their impact on subsequent analyses. Additionally, by analyzing user IDs, questionnaire submission times, and response consistency, three duplicate submissions were identified and removed to ensure data independence. After these procedures, 492 valid questionnaires and 50 in-depth interview records were retained, deemed high-quality, complete, and consistent, and suitable for further analysis.

2.3. Data Coding

After data cleaning, the next step involved coding the data, particularly converting qualitative data (e.g., interview transcripts and open-ended survey responses) into quantitative form.

2.3.1. Qualitative Data Coding

Responses to open-ended questions in interviews and surveys were converted into categorical variables. For example, user attitudes toward sustainable products (positive, neutral, negative) were coded into three categories: 1, 2, and 3. Similarly, behavioral motivations (e.g., cost-saving, environmental awareness, social responsibility) were also coded as categorical variables to facilitate subsequent statistical analysis.

2.3.2. Standardization of Numerical Data

For continuous variables such as energy usage and resource consumption, the Z-score standardization method was applied. This process adjusted each variable to have a mean of 0 and a standard deviation of 1, eliminating dimensional differences between variables and ensuring equal influence in the analysis.

2.3.3. Coding Results

The coded dataset included multiple categorical variables (e.g., user behavior patterns, attitudes, and motivations) and standardized continuous variables (e.g., energy consumption, resource usage). These variables formed the basis for subsequent cluster analysis and principal component analysis (PCA).

2.4. Data Standardization

The Z-score standardization method was used in this study to process numerical data, transforming each variable into standardized values with a mean of 0 and a standard deviation of 1. This treatment eliminated dimensional differences between variables, ensuring greater comparability and interpretability in subsequent statistical analyses. For instance, energy usage and resource consumption, once standardized, allowed for more accurate identification of differences in user behavior patterns. The formula is as follows:

$$Z = \frac{X-\mu}{\sigma} \tag{1}$$

Where(X) is the original data value, (μ) is the mean of the variable, and (σ) is the standard deviation of the variable. This standardization process enabled the comparison and analysis of different variables on the same scale.

As a result, a standardized user behavior dataset was obtained, consisting of 492 questionnaire responses and 50 in-depth interview records. After cleaning, coding, and standardization, the data ensured completeness, consistency, and analyzability, providing a solid foundation for subsequent cluster analysis, PCA, and design strategy optimization.

2.5. User Behavior Analysis

Cluster analysis and principal component analysis (PCA) were employed to systematically identify and analyze user behavior patterns, constructing a multi-dimensional feature space for user behavior. The dataset covered behavioral characteristics in energy use, resource consumption, waste management, and product usage habits. The K-means clustering algorithm was selected for its advantages in handling large datasets and rapid convergence. Using K-means, the research team divided users into multiple clusters, ensuring clear distinctions between different groups. The optimal number of clusters was determined using the elbow method, with (K = 3). This method visually displayed the impact of different cluster numbers on the clustering results by plotting the relationship between the total sum of squared errors (SSE) and the K value.

Subsequently, principal component analysis (PCA) was used for dimensionality reduction to simplify data complexity and identify key features influencing user behavior (Figure 5). Under the condition of (K = 3), K-means clustering analysis was performed, and the effectiveness of the clustering results was validated using the silhouette score. The silhouette score was 0.41, indicating moderate clustering performance, with tight intra-cluster cohesion and clear inter-cluster separation

(Figure 2).

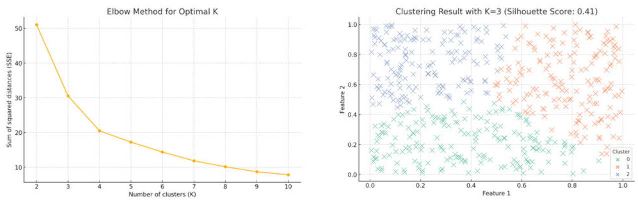

Figure 2. Elbow Method for Optimal K, Clustering Result with K=3(Silhouette Score: 0,41)

Cluster analysis revealed three main user behavior patterns: Pattern A consists of environmentally conscious users, who exhibit high self-discipline in energy use and resource consumption, actively adopting energy-saving measures and environmentally friendly products. Pattern B includes economically driven users, whose behavior is primarily motivated by economic factors; they tend to choose lower-cost products, even if these have a greater environmental impact. Pattern C comprises neutral or passive users, who show little concern for environmental or economic issues; their behavior is typically habit-driven, lacking proactive energy-saving or environmental awareness.

2.6. Principal Component Analysis (PCA)

Following the cluster analysis, principal component analysis (PCA) was employed to simplify the data. PCA reduces high-dimensional data to a lower-dimensional space while retaining most of the original data's variance. In this study, the first two principal components explained over 90% of the variance, making them sufficient for effective data analysis. These two components successfully captured the key information in the dataset and identified the core drivers of user behavior. PCA analysis clarified two primary driving factors: first, environmental and energy-saving awareness, which significantly influenced users' behavior in selecting energy-efficient products, resource consumption, and waste management; and second, economic considerations and consumption habits, indicating that users tend to make environmentally friendly choices when economic conditions allow, balancing price, durability, and consumption preferences.

Combined with the cluster analysis, user behavior was categorized into three main patterns: environmentally conscious, economically driven, and neutral/passive. The distribution of these patterns across different user groups reflects varying responses to and acceptance of sustainable design strategies, providing a theoretical basis for the development of subsequent design intervention strategies.

3. Construction and Evaluation of Sustainable Design Strategies

3.1. Construction of Design Strategies

Based on the analysis of user behavior patterns, this study developed sustainable design strategies tailored to different user groups, covering product design, spatial design, and system design, with customized adjustments according to the behavioral characteristics of users.

For the environmentally conscious user group, the design strategies focused on product durability and the use of renewable materials, such as modular and detachable furniture or electronics, to minimize resource waste. In spatial design, energy-efficient and green landscapes were emphasized, employing passive energy-saving technologies and ecological design elements such as high-efficiency insulation, natural lighting, vertical greenery, and rooftop gardens to further enhance environmental awareness. In system design, the development of smart resource management systems and sustainable community networks helps users monitor and manage their energy consumption in real-time, promoting resource sharing and circular economy models at the community level.

For the economically driven user group, the design strategies prioritized cost-effective energy-saving products and low-maintenance solutions to meet users' demands for price and cost-effectiveness. For example, the design of moderately priced high-efficiency energy-saving appliances balanced initial purchase costs with long-term energy savings. In spatial design, cost-effective energy-saving solutions, such as energy-efficient lighting and double-glazed windows, were preferred to reduce energy consumption without incurring significant upfront investment. Additionally, the development of budget-friendly smart control systems and discount incentive programs can help users manage household energy consumption at a minimal cost, while encouraging the adoption of energy-saving technologies and products through electricity bill discounts or reward points.

For the neutral or passive user group, the design strategies focused on simplifying processes and gradually guiding users to develop environmental awareness. In product design, emphasis was placed on environmentally friendly products that are easy to use, such as highly automated waste sorting equipment to reduce the difficulty of waste separation. Spatial design integrated seamless green technologies and convenient green channels, such as smart lighting systems, electric bike stations, and waste recycling points, to help users naturally reduce energy consumption in their daily lives. In system design, a progressive environmental education system and a user behavior feedback system were developed to encourage users to adopt sustainable practices through gamified applications and reward mechanisms, gradually improving their behavior over time.

3.2. Evaluation of Design Strategies

To assess the effectiveness of the developed design strategies, this study adopted a combination of scenario simulations and user experiments. The study utilized virtual reality (VR) and computer simulation technologies to evaluate users' behavioral responses in different design scenarios.

This study used Oculus Rift S and HTC Vive Pro devices to create virtual environments, providing high-resolution visuals and precise motion tracking for natural user interaction within the virtual environment. Through VR technology, the research team simulated user behavior responses in different spatial layouts, observing changes in energy usage habits. However, there are inherent differences between virtual environments and real-life scenarios, which may affect the external validity of the study results. Specifically, factors such as lighting, spatial perception, and interaction methods in virtual environments may differ from real life, leading to discrepancies between user behaviors in virtual environments and in reality. Therefore, while the virtual environments were designed to closely resemble real-life settings, it is important to acknowledge the potential biases these differences may introduce.

Behavior simulation testing was based on user behavior models developed using MATLAB and Unity platforms, which allowed researchers to analyze users' adaptability to design strategies and their behavioral changes. Although these models effectively simulated user behavior responses, tests conducted in virtual environments may not fully reflect users' actual behaviors in real life. To mitigate this, participants underwent thorough training to minimize biases resulting from unfamiliarity with or discomfort in using VR equipment. Future studies could consider combining virtual environment testing with validation experiments in real-world settings to improve the reliability and applicability of the results. The experiment recruited 60 participants, divided into three user groups: environmentally conscious, economically driven, and neutral/passive, with 20 participants in each group. Before the experiment, participants received necessary training to familiarize themselves with the VR equipment and simulated environment. The experiment simulated 10 different residential layouts, incorporating energy-saving features such as energy-efficient lighting, natural lighting, and smart temperature control systems, to assess the practical effectiveness of the design strategies.

3.3. User Experiments

In the user experiments, the research team conducted tests on products and systems in both laboratory and real-life environments, collecting user feedback on usage, including changes in energy consumption, user satisfaction, and behavior improvement. Subsequently, statistical methods such as multiple regression analysis and ANOVA were used to conduct an in-depth evaluation of the impact of design strategies on user behavior.

The multiple regression data model is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \epsilon \quad (2)$$

Where (Y) represents energy consumption, (X1,X2,...,Xn) represent the use of different design strategies and user behavior characteristics, (β_1, β_2, ...,β_n) are the regression coefficients, and (ϵ) is the error term.

The results of the multiple regression analysis showed that certain design strategies (such as smart lighting systems) had higher regression coefficients, with a significance level of 0.01, indicating a significant impact on energy consumption. Other strategies (such as the timer switch function) had lower or non-significant regression coefficients, suggesting the need for optimization. Through graphical analysis of the regression coefficients and standard errors, it was shown that the effects of design strategies, operation frequency, and user behavior patterns on energy consumption varied. Notably, user behavior patterns (regression coefficient = 4.7397) and operation frequency (regression coefficient = 3.3133) had particularly significant impacts on energy consumption. The model's R-squared value was 0.762, indicating that the model explained approximately 76.2% of the variation in energy consumption, demonstrating a good fit. Additionally, the P-values of all independent variables were less than 0.05, showing their significant impact on energy consumption.

Overall, these analysis results indicate that different design strategies and user behavior patterns have significant differences in their energy-saving effects. Therefore, based on these findings, design strategies can be optimized for specific user groups to achieve energy-saving goals more effectively.

Specifically, the median energy consumption for the environmentally conscious user group was lower when utilizing energy-saving strategies, while the neutral or passive user group had a relatively higher median energy consumption. The ANOVA results showed an F-value of 9.71 and a P-value of 0.0001, indicating that the impact of different user behavior patterns on energy consumption was statistically significant (P-value < 0.05). These findings demonstrate that user behavior patterns have a significant influence on the effectiveness of design strategies, with different user groups responding differently to the same energy-saving strategies. Therefore, design strategies need to be customized according to the behavior patterns of different user groups to achieve optimal energy-saving outcomes. Through this approach, the design strategies in this study were systematically validated and optimized, ultimately providing customized sustainable design solutions for different user groups, helping them achieve energy-saving and environmental goals more effectively in their daily lives and work.

3.4. Development and Experimental Validation of Design Intervention Strategies

3.4.1. Development of Design Intervention Strategies

This study developed various design intervention strategies aimed at directly guiding users toward more environmentally friendly behaviors through visual prompts, interactive feedback, and behavioral incentives. These strategies incorporated theories of user behavior, taking into account users' psychological responses, habits, and motivations to ensure that the interventions effectively and sustainably influence behavior. Specific strategies include adding clear visual prompts to product and system interfaces (e.g., labeling energy consumption levels and displaying real-time energy data) to remind users with weaker environmental awareness and less initiative to pay attention to energy usage, thereby stimulating their environmental consciousness. Instant feedback systems were used to show users the impact of their actions on energy consumption, enhancing environmental responsibility for those who are sensitive to operational outcomes and prefer immediate feedback, and promoting energy-saving behavior through positive reinforcement. Economic incentives such as reward points or cost reductions were introduced to encourage economically motivated users to actively engage in energy-saving actions, driving them to adopt more proactive energy-saving behaviors.

3.4.2. Experimental Validation of Design Intervention Strategies

To validate the practical effectiveness of these design intervention strategies, the research team designed and implemented an experiment. A total of 100 users were recruited and divided into four groups: the visual prompt group, the interactive feedback group, the behavioral incentive group, and the control group (with no intervention). The experiment was conducted in simulated household or office environments, with each group using devices equipped with the corresponding intervention strategy. During the experiment, user data were recorded, including operation frequency, operation duration, system usage, and energy consumption monitored through smart meters. The effectiveness of each intervention strategy was evaluated by combining these data with user feedback.

The results showed that different design intervention strategies had significant effects on user operation frequency and energy consumption. The operation frequency in the visual prompt group increased by 15%, with a 10% reduction in energy consumption; the interactive feedback group saw a 20% increase in operation frequency and a 15% reduction in energy consumption; and the behavioral incentive group achieved a 25% increase in operation frequency and a 20% reduction in energy consumption. In contrast, the control group showed no significant changes. Furthermore, user satisfaction surveys revealed that the behavioral incentive group had the highest satisfaction rate at 90%, followed by the interactive feedback group at 85%, the visual prompt group at 80%, and the control group at 70%.

The results indicate that the behavioral incentive strategy was the most effective in motivating users to adopt energy-saving actions and demonstrated significant energy-saving results in practical applications. While interactive feedback and visual prompt strategies also had some effect, they were relatively weaker. The behavioral incentive strategy not only resulted in significant reductions in energy consumption but also achieved the highest user satisfaction, highlighting its broad acceptance as an energy-saving strategy.

4. Results Analysis and System Optimization

4.1. Data Analysis Methods

To assess the impact of different design intervention strategies on user behavior, this study employed analysis of variance (ANOVA) and multiple regression analysis. Through these methods, the study explored the actual effects of each intervention strategy on user behavior and energy consumption, and used this information to optimize the design strategies. ANOVA was used to compare behavior changes across different user groups after implementing the various design intervention strategies, assessing the significance of these changes. Multiple regression analysis was employed to quantify the impact of each strategy on energy consumption and to identify the most influential strategies.

4.2. Data Analysis Results

The ANOVA results showed an F-value of 9.71 and a P-value of 0.0001, indicating that the effects of different user behavior patterns and intervention strategies on energy consumption were statistically significant. In particular, the behavioral incentive strategy stood out in terms of increasing operation frequency and reducing energy consumption. Multiple regression analysis further confirmed these findings, with an R-squared value of 0.762 for the regression model, suggesting that the model explained 76.2% of the variance in energy consumption. The P-values for all independent variables were less than 0.05, indicating that these variables had significant effects on energy consumption.

Through this data analysis, the study identified the effectiveness of each design strategy in practical applications and provided a basis for further system optimization. Specifically, the behavioral incentive strategy had the most significant positive impact on user behavior, suggesting that it should be prioritized in future design practices.

4.3. System Optimization

Based on the experimental results, this study conducted system optimization for the design strategies and interventions, ensuring their general applicability and effectiveness across different user groups. A dynamic optimization framework for design strategies was developed, allowing for real-time adjustments based on varying contexts and user feedback to achieve optimal sustainability outcomes.

Specific system optimization recommendations include enhancing the behavioral incentive strategy by increasing the types and value of rewards to further boost the attractiveness of the point-based reward system, thereby motivating users to engage more actively in energy-saving actions. The visual prompt and interactive feedback strategies were optimized by offering more personalized prompts and enhancing the immediacy and visualization of feedback, making it easier for users to understand the specific impact of their actions on energy consumption. Additionally, design intervention strategies were customized according to user behavior patterns. For example, combining visual prompts with behavioral incentives can gradually cultivate energy-saving habits in users with weaker environmental awareness. These analyses and system optimization recommendations provide scientific support for future sustainable design practices, ensuring that the design strategies not only achieve energy-saving goals but also gain broad user acceptance and recognition.

5. Discussion

This study systematically validated the impact of different design intervention strategies on user behavior and energy consumption through experiments conducted in simulated smart living spaces. Participants were randomly assigned to four groups, each implementing strategies such as visual prompts, interactive feedback, and behavioral incentives, with smart devices automatically collecting data. The results indicated significant differences in the effectiveness of these strategies in increasing user engagement in energy-saving actions and reducing energy consumption.

The behavioral incentive strategy was the most effective, significantly increasing user operation frequency and reducing energy consumption by an average of 20%, with a user satisfaction rate of 90%. This demonstrates the strong motivating power of economic incentives for energy-saving behavior and its high level of user recognition. The interactive feedback strategy reduced energy consumption by 15%, with an 85% satisfaction rate, showcasing the effectiveness of guiding user behavior through real-time feedback. Although the visual prompt strategy had a weaker effect, reducing energy consumption by 10%, it still achieved an 80% satisfaction rate, indicating that the strategy has a role in raising user awareness of energy saving.

However, beyond statistical significance, the practical implications of these results warrant further discussion. For instance, a 10-20% reduction in energy consumption has varying impacts depending on the total energy usage in the specific application scenario. In residential or office environments, such energy savings can translate into actual cost savings and reduced carbon emissions, particularly when applied on a larger scale. These energy-saving effects have the potential to positively impact both individual users and society at large. Therefore, when evaluating energy-saving strategies, it is important to consider not only their statistical significance but also their practical impact on everyday energy use.

Further ANOVA and multiple regression analyses confirmed the statistical significance of these intervention strategies, particularly highlighting the strong impact of behavioral incentives on reducing energy consumption. It is important to note, however, that the effectiveness of different strategies may vary across user groups. Customizing energy-saving strategies to meet specific user needs can lead to more effective outcomes. For example, behavioral incentives may be more attractive to economically driven users, while visual prompts may be more suited to users with weaker environmental awareness.

Additionally, the research suggests that combining different strategies in future sustainable design efforts could lead to greater energy-saving outcomes. For instance, combining visual prompts with behavioral incentives could better guide users with weaker environmental awareness to adopt energy-saving behaviors. Such strategy combinations not only create synergistic effects in various scenarios but also enhance both energy-saving outcomes and user satisfaction. Therefore, future research should continue to explore the combined application of these strategies and validate their effectiveness in broader real-world environments, providing more comprehensive and effective guidance for sustainable design.

6. Conclusion

This study experimentally validated the impact of behavioral incentives, interactive feedback, and visual prompts on user behavior and energy consumption, revealing significant differences in the effectiveness of each strategy in energy-saving practices. Behavioral incentives proved to be the most effective, significantly increasing user engagement in energy-saving actions and reducing energy consumption by approximately 20%, while also achieving the highest user satisfaction. This highlights the effectiveness of economic incentives in promoting energy-saving behavior and their widespread acceptance among users.

Although interactive feedback and visual prompts were less effective, they still contributed to raising user environmental awareness and reducing energy consumption. Interactive feedback, through real-time mechanisms, helped users better understand the impact of their actions on energy consumption, achieving a 15% reduction in energy use. Visual prompts guided users toward energy-saving modes through intuitive displays, reducing energy consumption by 10%. These results indicate that the effectiveness of design strategies depends on their ability to stimulate intrinsic motivation and behavioral change in users.

ANOVA and multiple regression analyses further confirmed the statistical significance of these strategies, particularly emphasizing the strong impact of behavioral incentives on energy consumption. These findings provide a theoretical foundation and practical guidance for future sustainable design, suggesting that intervention strategies should be customized according to different user behavior patterns to achieve better energy-saving outcomes. Future research should continue to explore the long-term effects of these strategies and investigate the combined application of different strategies to maximize energy-saving results.

References

[1] Santin, O. G., Itard, L., & Visscher, H. (2009). The effect of occupancy and behaviour on energy consumption in dwellings. Building Research & Information, 37(5), 555-567.

[2] Gram-Hanssen, K. (2010). Residential heat comfort practices: Understanding users. Building Research & Information, 38(2), 175-186.

[3] Laitala, K., & Boks, C. (2012). Sustainable clothing design: Use matters. Journal of Design Research, 10(1/2), 121-139.

[4] Thøgersen, J. (2014). Unsustainable consumption: Basic causes and implications for policy. European Psychologist, 19(2), 84-95.

[5] Mont, O., & Plepys, A. (2008). Sustainable consumption progress: Should we be proud or alarmed?. Journal of Cleaner Production, 16(4), 531-537.

[6] Manzini, E., & Vezzoli, C. (2003). A strategic design approach to develop sustainable product service systems: Examples taken from the 'environmentally friendly innovation' Italian prize. Journal of Cleaner Production, 11(8), 851-857.

[7] Thøgersen, J. (2006). Norms for environmentally responsible behaviour: An extended taxonomy. Journal of Environmental Psychology, 26(4), 247-261.

[8] Steg, L., & Vlek, C. (2009). Encouraging pro-environmental behaviour: An integrative review and research agenda. Journal of Environmental Psychology, 29(3), 309-317.

[9] Lockton, D., Harrison, D., & Stanton, N. A. (2010). The design with intent method: A design tool for influencing user behaviour. Applied Ergonomics, 41(3), 382-392.

[10] Bhamra, T., & Lofthouse, V. (2007). Design for sustainability: A practical approach. Gower Publishing, Ltd.