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Evaluation of Wood Coverage on Building Facades Towards Sustainability

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Abstract: This study explores the acceptance of different wood coverages on building facades with the aim of optimization of materials, and in turn improving overall sustainability. It firstly develops the principal physical variables and evaluation criteria; then, test models are created using an orthogonal design experiment; finally, two evaluation methods are used to comprehensively test acceptance, based on a questionnaire and an eye-tracking study. The results show that: (1) The effects of the amount of wood coverage and the wood patterns are significant, whereas the effect of material combinations is insignificant. (2) The acceptance of building facades is at the highest level when the amount of wood coverage is 65%. (3) The amounts of wood coverage for facades in the range of 35% to 50% are effective when designing the facade of wood buildings, in order to implement the dual targets of saving wood and higher acceptance.

Keywords: acceptance; wood coverage; building facade; eye-tracking; wood building; sustainability

1. Introduction

In the context of global warming, the avoidance of building waste is of urgent concern [1]. Wood itself is a sustainable and carbon-negative material, which is beneficial for improving people's well-being [2–6]. In this context, wood is widely utilized in the material-intensive sectors of construction and furniture due to its green ecological and bio-friendly material advantages [7–9]. However, the development of wood construction is making wood supply and demand in China more and more intensive. A large amount of wood is imported from abroad every year, and wood resource shortages have become a major obstacle to development [10]. To reduce construction costs and make use of wood both intensively and efficiently, it is essential to study optimal wood consumption in combination with other materials to improve the sustainability of the built environment. Also, the evaluation of the visual preference for wood has become a strong area of research [11,12].

Masuda studied the influence of knots on the perceptions of wood panel facades [13]. Masuda and Yamamoto also studied how indoor wood coverage correlated with human emotion. They found that there was no positive linear relationship for the description of "warm" for indoor spaces with the increase of indoor wood coverage; instead, there was a best proportion relationship [14]. Masuda and Nakamura then reconstructed the study, focusing on the descriptors "natural" and "novel". It was found that the relationship between the amount of wood coverage and "novel" was significant. Rooms with wood coverages approaching either zero or 100% were seen as the most novel. The wood coverage relationship with "novel" (U-shaped) was the opposite of the "warm" relationship (upside down U-shaped) [15]. Tsunetsugu et al. measured the psycho-physiological reactions of

subjects who entered rooms with different wood coverages, and the test results showed that the room with 45% wood coverage was the space most complimented by the subjects [16]. Other studies have also suggested that specific aspects of wood, such as color, quantity, and grain pattern, influence stress and stress recovery [17,18], revealing that there is a relationship between the amount of wood coverage and the preference for wood. Robert showed that wood provided stress-reducing effects similar to the well-studied effects of exposure to nature in the field of environmental psychology [11]. In 2017, Cronhjort et al. used questionnaires, interviews and observations on site to explore the preference of selected office spaces, including different amounts of wood-based materials on various interior elements, and surveyed the preference of wood in care environments [19]. However, most of the previous research so far has focused specifically on indoor spaces, whereas building facades are one of the more important components of urban spaces. Some studies have considered the restorative potential of more specific urban settings, and research has adequately addressed how specific architectural characteristics of urban residential settings might serve psychological restoration [20,21]. Although existing studies have shown that people's preferences are significantly influenced when applying wood in urban spaces, wood mostly functions as a landscape element, such as wooden walkways in city parks or wooden furniture in pedestrian streets [22,23]. Thus, as a major constituent of the enclosed interface of urban space, it is important to evaluate preferences for the use of wood for building facades.

Korpelainen and Ikei reviewed the academic literature on wood as a visual material, published in the last 30 years [18,24]. Korpelainen focused on wood and human stress in the built indoor environment, and Ikei focused on the physiological effects of wood on humans. Among those studies, a questionnaire research method was widely used, and most of the target group of the questionnaire were students with an age from 20 to 30 years. Although visual attention's effect on participant decisions had been studied, research utilizing eye-tracking technology to investigate the relationship between consideration of wood visual stimuli and participant preferences was scarce. Nakamura et al. used eye-tracking technology to investigate the visual impact of knots, but the present study is the first to objectively quantify the visual inducement of knots [25]. However, eye-tracking studies have been widely used in the field of product marketing and advertising design [26]. Behe et al. used eye-tracking technology with conjoint analysis and determined that consumers spent more time visually considering important plant attributes [27]. Furthermore, Rihn et al. used eye-tracking technology to investigate consumers' purchase likelihoods and visual search behavior for aesthetic and food-producing ornamental plants [28]. Visual attention was connected to participants' decision-making processes and choices [29–32]. Behe et al. demonstrated a correlation between visual consideration and consumers' choice behavior [27,33].

This research therefore aims to explore the effectiveness of wood use on building facades. More specifically, the key research question is to find out the acceptable wood coverage for applying wood resources more efficiently. This study used questionnaire, eye-tracking study, and interview to conduct subjective and objective exploration of the topic.

2. Methods

Figure 1 shows the research framework, including both qualitative and quantitative approaches, which are described in the following sections in more detail.

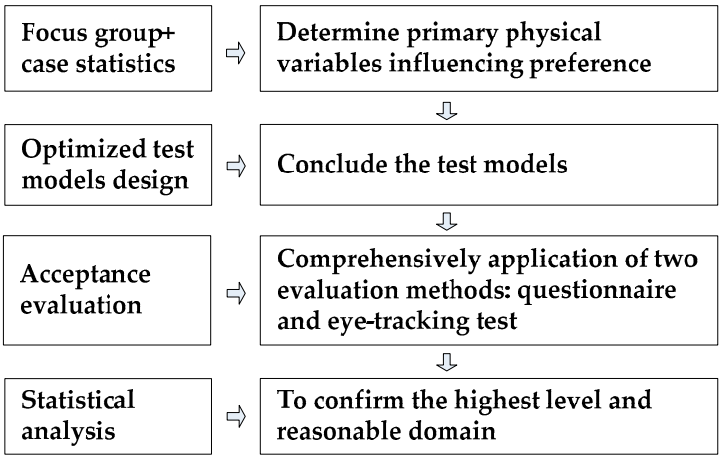

Figure 1. Research framework.

2.1. Physical Variables

We first developed the main physical variables influencing wood building preference with the help of a focus group discussion. As the literature showed that it was effective to organize 6 to 12 people in a focus group discussion [34,35], ten graduate students of Harbin Institute of Technology (including 1 host and 1 recorder of the meeting, and 5 men and 5 women with an age from 20 to 30 years) with a relatively strong academic background in wood architectural design and environment-behavior psychology studies participated in discussions. The host guided the discussion of topics prepared in advance. The focus group selected the physical variables on which to base this study. Then, based on a statistical analysis of existing wood buildings, the principal physical variables and different levels were confirmed [36], as shown in Table 1.

Table 1. Principal physical variables and levels influencing preference of wood facades.

Physical Variables		
Wood Coverages (%) A	**Material Combinations B**	**Wood Patterns C**
1:80	1: White plaster	1: Plain
2:65	2: Concrete	2: With lines
3:50	3: Stone	3: With dots
4:35		
5:20		
6:5		

2.2. Optimized Test Model Design

To study the correlation between the preference of wood building and wood physical variables on building facades, the orthogonal experiment method was used for this study, which is highly efficient for dealing with multivariable and multilevel experiments. Compared to the comprehensive experiment containing 54 test models, only 18 models would be representative. Before making the orthogonal design table, principal variables and levels were determined by a focus group discussion and statistical analysis of existing wood buildings as $6^1 \times 3^2$, including 3 variables and 6 levels of variable A, 3 levels of variables B and C (see Table 1). It was assumed that any two variables would not interact with each other. Therefore, after a parallel transformation of an orthogonal table $L_{18}(3^{17})$, a mixed orthogonal table $L_{18}(6^1 \times 3^{12})$ was finally confirmed for the design models, as shown in Table 2. In the orthogonal experimental method, the primary and secondary relationships between variables and indexes can be presented by variance statistics [37,38].

In Table 2, 1′, 6′, and 8′ in the column headers represent that variables A, B and C all have multiple freedoms. The number of freedoms is determined by the level of variable (=$N - 1$). So in this study, variable A has 5 freedoms and variables B and C have 2 freedoms each. Thus, in the orthogonal table, 1′ represents all the items for variable A, 6′ represents all the items for variable B, 8′ represents all the items for variable C.

As this research aims to find the amount of wood coverage on building facades that is preferred, in order to prevent unnecessary disturbances in testing the preference of the use of wood on building facades, it was decided, based on a focus group discussion, to design a single building as a test object, with a simple shape and designed using basic aesthetic principles, ensuring the same window–wall ratio, window form, and surroundings. Using SketchUp8 software (Google) [20], five postgraduate students independently created designs for the survey. The research team then optimized the test buildings for the survey, as can be seen in Table 2. The design models were made of laminated timber with a natural light yellow color, which is the most widely used in construction. In more detail, cross-laminated timber (CLT) for plain patterns, nail-laminated timber (NLT) for wood patterns with lines, and laminated strand lumber (LSL) for wood patterns with dots were simulated to develop a more realistic virtual modelling. It is noted that because of the limitations in using stone as a building material when the amount of wood coverage is 5%, we excluded one of the original designs, and therefore, 17 test photos were used in the final survey.

Table 2. Test models.

Test No.	Physical Variables			Photos	Test No.	Physical Variables			Photos
	A	B	C			A	B	C	
	1′	6′	8′			1′	6′	8′	
1	1	1	3		10	4	1	3	
2	1	2	1		11	4	2	1	
3	1	3	2		12	4	3	2	
4	2	1	1		13	5	1	1	
5	2	2	2		14	5	2	2	
6	2	3	3		15	5	3	3	
7	3	1	2		16	6	1	2	
8	3	2	3		17	6	2	3	
9	3	3	1		18	6	3	1	/

2.3. Acceptance Evaluation

Two evaluation methods—a questionnaire and an eye-tracking study—were used to explore the relationship between preference for wood building facades and different wood coverages.

2.3.1. Questionnaire

With the help of a focus group discussion, evaluation indexes for the questionnaire were confirmed, as shown in Table 3. Three of the items would fall into the "visual" category, and three items would fall into the "perceptive" category. The visual category was used for the measurement of whether the amount of wood coverage was suitable, whether the material combination was coordinated, and whether the wood pattern was aesthetically pleasing. The respondents' perceptions of the test photos were obtained by asking the following three questions: (1) Does the design make you feel comfortable and relaxed? (2) Does the design attract you, that is, make you want to spend time close to this structure? (3) Do you think that the structure meets practical function and would be your priority selection?

Table 3. Survey dimensions and evaluation indexes.

Dimensions	Items	Evaluation Indexes
Visual aspects	Amount of wood coverage	Suitable
	Material combination	Coordinated
	Surface pattern of wood	Appropriate
Perceptive aspects	Effect on restoration of the test subjects	Relaxed and "natural" feel
	Attraction to the structure	Want to be close
	Associate practical function with architectural appearance	Priority selection

A questionnaire was designed with six items to measure subjective preferences, with a 7-point scale (0 = not at all; 6 = completely). The respondents rated each of the images on six items. The target respondents were aged 20–30 years, with approximately equal numbers of men and women. There was no limitation with regard to their professions. With 67 taped video surveys in total, and after viewing the videos, 60 valid questionnaires were selected.

The test subjects of most of the previous research on the perceptions of indoor wood space were with an age from 20 to 30 years [18,24]. In order for the results to be comparable with the findings of other studies, the participants of the focus group discussion and the respondents of the questionnaire and the following eye-tracking study for this research were all aged 20–30 years, accordingly.

2.3.2. Eye-Tracking Study

Eye-tracking study provides one of the most powerful means by which the processes driving individuals' choices can be uncovered. Eye-tracking metrics provide insights into subjects' behavior, which are concise attribute measurements [32,39]. The eye-tracking study was conducted in the Harbin Institute of Technology Environmental Psychology Laboratory. The participants were 12 men and 12 women who were recruited from among the students of Harbin Institute of Technology. The relatively homogeneous samples would eliminate some interference [11].

Firstly, six test photos (1750 × 1900 pixels) were prepared on one page, according to orthogonal experiment models. The group photos were then input into a computer with image display. The participants were able to look at the computer screen with each group of photos for 15 s. This short observation time was defined to prevent the subject from becoming bored and to record sufficient eye-mark data for the analysis [25]. They could observe the photos freely and their eye-tracking data for the different test photos could then be examined and analyzed.

The study measured the number of fixations and average fixation durations for different pictures present on the screen sites as an indicator of awareness [40]. The test data showed participants' different level of attention, where longer fixation duration and higher numbers of fixations represented more concentrated attention.

The procedures for the eye-tracking study, as shown in Figure 2, were as follows [28]: Step 1, calibrate the Tobii TX300 Eye Tracker; Step 2, calibrate the participant's eye position, confirming the participant's eye movements to be accurately monitored, and then enter the participant's name; Step 3, display the group of photos on the computer screen in front of the participant for 15 s for each test session, during which the participant is free to explore the image presented; Step 4, save the eye-tracking data.

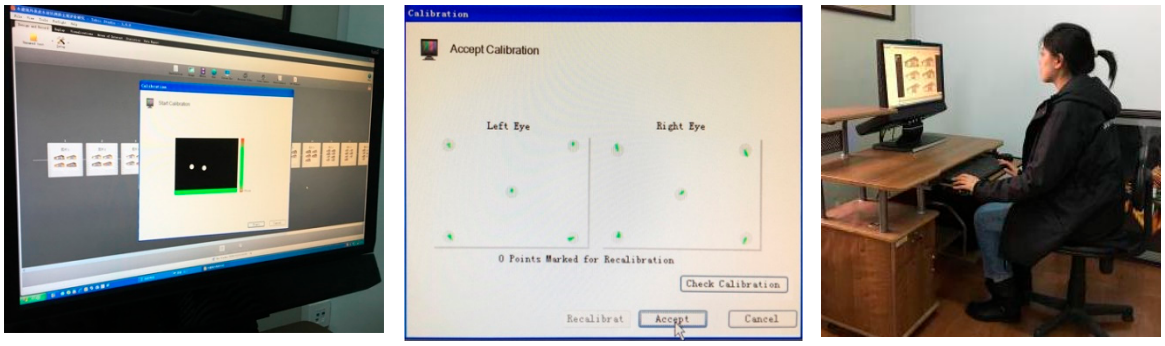

Figure 2. Scene photos of the eye-tracking test.

2.4. Statistical Analysis

In the present study, the images of buildings are the units of analysis. The physical variables used in the analysis reflect variability with respect to the level of wood coverage, with the values of the physical variables resulting from researcher manipulations. The subjective preferences (S) were measured using participant ratings (with a total of 60 test cases); the mean of their ratings for each image was used for further analysis. The objective preferences (O) were measured with eye-tracking study (total of 24 test cases) using the weighted average of the mean of their fixation duration and the number of fixations for each image. Analyses were completed using SPSS 22.0 software.

The mean value of the main targets before and after the wood coverage changed, such as the preference and acceptance, were compared and analyzed. The analysis of variance showed the influence of different wood coverages, material combinations and wood patterns on preference of wood building facades, trying to find out the most influential item. The paired sample *t*-test was applied.

3. Results

3.1. Significance Analysis of Physical Variables

The results of the significance analysis of the variables are shown in Tables 4 and 5. Taking the mean value of respondents' ratings for each image as a parameter, Table 4 shows that there were significant effects of variable A (wood coverage) and variable C (wood patterns) on the acceptance of wood building facades ($p = 0.04$), but the effect of variable B (material combinations) was insignificant ($p = 0.76$). Based on the comparison of value F, it shows that the primary and secondary order of each physical variables was C > A > B. Table 5 shows the mean value of respondents' ratings for each image in the questionnaire. Based on the comparison of value K, it shows the highest evaluation item for variable A, which was A_2 (65%). The highest evaluation item for variable C was C_2 (with lines), whereas the evaluation value for B_1, B_2 or B_3 did not show much difference. Thus, the best variable combination for wood building facades was the case of A_2BC_2.

Table 4. Variance analysis of physical variables.

Physical Variables	Sum of Squares	df	Mean Square	F	Sig.(2-Tailed)
A	4.58	5	0.92	3.36	0.04 *
B	0.29	2	0.15	0.28	0.76
C	2.84	2	1.42	4.20	0.04 *

* significant level at 0.05.

Table 5. Evaluation of each parameter.

Test No.	Mean Value of Ratings	Test No.	Mean Value of Ratings	Test No.	Mean Value of Ratings
1	2.57	7	3.49	13	2.80
2	3.38	8	2.61	14	2.41
3	3.69	9	3.35	15	1.78
4	3.45	10	2.38	16	2.46
5	4.14	11	3.04	17	1.66
6	3.39	12	3.55	18	/
K_{A1} = 9.64; K_{A2} = 10.97; K_{A3} = 9.45; K_{A4} = 8.97; K_{A5} = 6.99; K_{A6} = 4.12					
K_{B1} = 17.15; K_{B2} = 17.23; K_{B3} = 15.76					
K_{C1} = 16.02; K_{C2} = 19.73; K_{C3} = 14.39					

3.2. Preference of Different Wood Coverages on Building Facades

Figure 3 shows the evaluation mean value of different wood coverages according to the questionnaire and the eye-tracking study. It can be seen that the mean of subjective rating of preference (S = 3.66) was the highest when wood coverage was 65%, fixation time (T = 4.21 s) was the longest when wood coverage was 65%, and the number of views (*N* = 5.81) was the highest when wood coverage was 50%. Table 6 shows the preference of different wood coverages on building facades. Subjective preference peaked when wood coverage was 65%, while objective preference peaked when wood coverage was 50%.

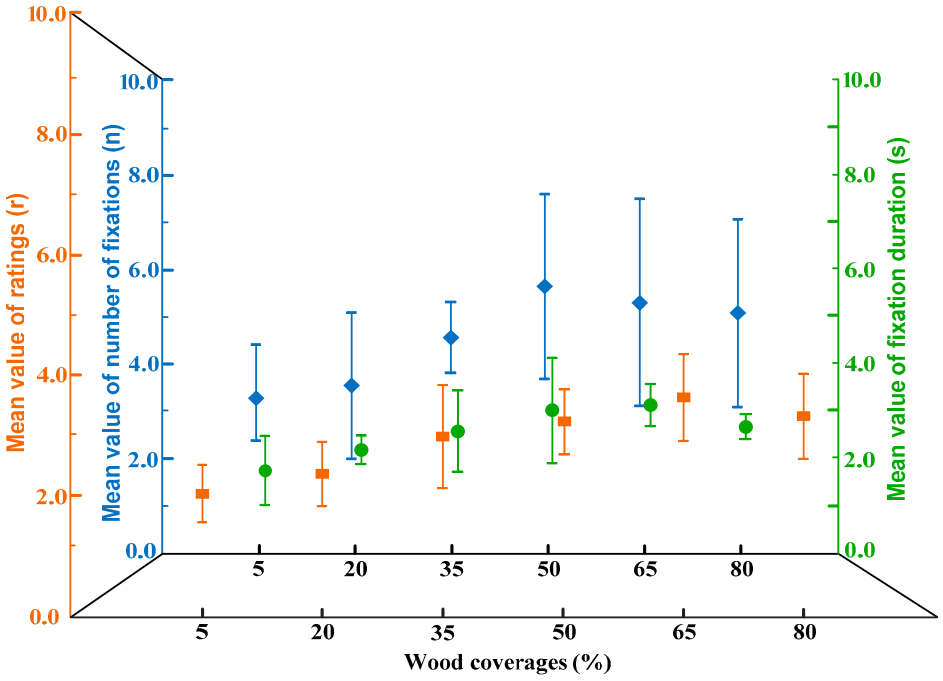

Figure 3. Preference descriptive index of different wood coverages according to questionnaire and eye-tracking study.

Table 6. Preference of different wood coverages.

Wood Coverages (%)	5	20	35	50	65	80
Subjective preference (S)	2.06	2.33	2.99	3.15	3.66	3.21
Objective preference (O)	2.83	3.25	3.97	4.91	4.77	4.37

A brief interview was held after the completion of the test, to make further confirmation. One interviewee stated that "People have a feeling of being close to nature" when the amount of wood coverage on building facades was 50% and 65%. The interviewee further stated, "It seems that the building is not a wood building any more when the amount of wood coverage is less than 20%, the wood becomes more like just a decorative element." A common feeling was that when the amount of wood coverage reached 80%, the building lost some sense of the "natural" due to the lack of comparison among different materials; Instead, there was an "unbreathable" feeling. Over 68% of the interviewees agreed with this viewpoint.

3.3. Correlation between Acceptance of Wood Building and Wood Coverage on Building Facades

The acceptance of wood building facades is a comprehensive reflection of subjective and objective preference, which could be expressed as $M = (S + O)/2$, where M represents the acceptance, S represents the subjective preference, and O represents the objective preference. Table 7 shows the acceptance of different wood coverages on building facades. It can be seen that the acceptance was at the highest level when the amount of wood coverage was 65%.

Figure 4 shows the variation trend of acceptance with the increase of wood coverage. It can be seen that acceptance increased with the increase of wood coverage, with a peak when wood coverage was 65% and then decreased with further increase of wood coverage.

Table 8 shows the increased degree of acceptance with an increase of 15% wood coverage. It can be seen that acceptance increased by 5.18, 10.35 and 8.25 at the level of $p < 0.05$ when the wood coverage was increased from 5% to 50%, respectively. Acceptance increased by 2.78 at the level of 0.18 when the wood coverage was increased from 50% to 65%. Acceptance declined by 6.38 at the level of 0.12 when the wood coverage was increased from 65% to 80%. This indicates that acceptance would be significantly improved by an increase of wood coverage if the amount of wood coverage were in the range of 5% to 50%. The increased degree of acceptance was insignificant with the increase of wood coverage when the amount of wood coverage was in the range of 50% to 65%. The acceptance began to decline once wood coverage was greater than 65%, and was insignificant. In consideration of the two indexes of acceptance and saving wood, the most reasonable values of wood coverage for building facades were determined to be in the range of 35% to 50%.

In sum, and consistent with findings of other studies, the results showed that wood is more subjectively preferred than other construction materials in the built environment, which is beneficial for sustainable development [17–19]. Similar to previous research, this study also showed that the preference for the amount of wood coverage on the facade of a building did not have a positive linear relationship with the increase of wood coverage. Instead, there was a best proportion [15,41]. While studies of wood amounts used in indoor spaces, providing participants with six visual surfaces, found that the most pleasing amount of wood coverage for indoor spaces was approximately 45% [16], the present study showed that the visual effect was the best when the amount of wood coverage on outdoor facades was 65%. In other words, these results showed that there was a higher preference for wood coverage on building facades than for indoor wood applications. This study extended the application possibilities of wood on building facades. Previous research has focused on the impact of a single variable [11,16,19,42], while this study considered comprehensive influences of multiple variables, which would be more approaching to reality.

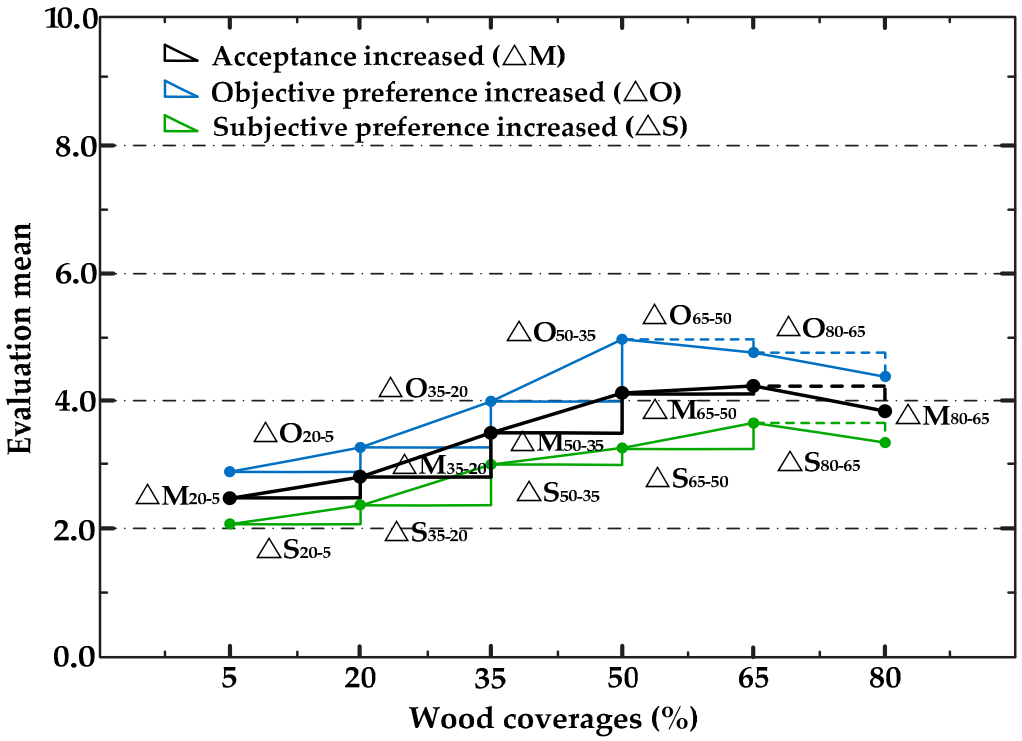

Figure 4. Variation trend of acceptance with the increase of wood coverage.

Table 7. Acceptance of different wood coverages.

Wood Coverages (%)	5	20	35	50	65	80
Acceptance (M)	2.45	2.79	3.48	4.03	4.22	3.79

Table 8. Increased degree of acceptance with the increase of wood coverage.

Acceptance: ΔM = (ΔS + ΔO)/2							
Wood Coverages %		ΔS	ΔO	ΔM	T	df	Sig.(2-Tailed)
Pared-samples 1	20–5	4.05	6.30	5.18	2.52	11	0.03 *
Pared-samples 2	35–20	9.90	10.80	10.35	2.77	20	0.01 *
Pared-samples 3	50–35	2.40	14.10	8.25	2.71	20	0.01 *
Pared-samples 4	65–50	7.65	−2.10	2.78	1.38	20	0.18
Pared-samples 5	80–65	−6.75	−6.00	−6.38	−1.61	20	0.12

* significant level $p < 0.05$.

4. Conclusions

This research shows that there is a significant correlation between acceptance of wood building facades and the amounts of wood coverage of the facades, and that acceptance of wood building facades was at the highest level when the amount of wood coverage was 65%.

The results of significance analysis of physical variables showed variable A (wood coverage) and variable C (wood patterns) were significant, while variable B (material combinations) was insignificant. The highest evaluation item for variable A was A_2 (65%), the highest evaluation item for variable C was C_2 (with lines), whereas the evaluation value for various variable B showed insignificant difference. Thus, the best variable combination for wooden facade performance of buildings was in the case of A_2BC_2.

The acceptance increased with the increase of coverage at a statistically significant level when the wood coverage was less than 50%, but when the wood coverage was great than 50%, the increased acceptance was insignificant. Finally, it was determined that wood coverage for facades in the range

of 35% to 50% is effective when designing facades for wood buildings, in order to achieve the dual targets of saving wood and higher acceptance.

To enhance research validity, more studies should be conducted in field settings outside the laboratory. In some settings, the results might differ among other physical variables like wood species and colors. In addition, more studies should be conducted in different building functions, such as in hospitals, schools, workplaces, nursing home, etc., and among persons of different ages and different health conditions. The perception could also be affected by other environmental factors [43]. Therefore, in the follow-up work, it is essential to conduct more longitudinal studies, to obtain a better and more comprehensive understanding of the research field.

Author Contributions: Conceptualization, H.X., J.L. and J.K.; Methodology, H.X., J.W. and J.K.; Software, J.L.; Validation, H.X., J.L. and J.W.; Formal Analysis, J.L.; Investigation, J.L. and J.W.; Resources, J.L.; Data Curation, J.L. and J.W.; Writing–Original Draft Preparation, H.X. and J.L.; Writing–Review & Editing, J.W. and J.K.; Visualization, H.X. and J.L.; Supervision, H.X. and J.K.; Project Administration, H.X.; Funding Acquisition, H.X.

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