sustainability

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Energy-Saving and Ecological Renovation of Existing Urban Buildings in Severe Cold Areas: A Case Study

Ying Liu [1,*], Depeng Chen [2], Jinxian Wang [2] and Mingfeng Dai [1]

[1] Faculty of Art and Design, Wan Jiang Institute of Technology, Ma'anshan 243000, China; 15755387833@163.com
[2] Architectural Engineering Institute, Anhui University of Technology, Ma'anshan 243032, China; 15855503077@163.com (D.C.); fm1990wjx@ahut.edu.cn (J.W.)
* Correspondence: wt16024@wjut.edu.cn

Abstract: High-rise buildings in cold regions have a requirement of ecological improvement due to the continuous response to climate change throughout the year. This study evaluates wind environment, light environment, thermal environment, and energy consumption environment using Phoenics, Ecotect, and DesignBuilder tools, utilizing a high-rise residential building in an intensely cold place as an example. With the goal of repairing the buildings, green energy-saving measures are applied from the perspectives of form, structure, system, and equipment strategy. The energy-saving rates and carbon dioxide emission reduction rates of the renovated buildings were predicted. The results reveal that, in the building performance diagnostic, the wind speed clearly rise at the building's corner, particularly on the outdoor level and the top floor; meanwhile, the inside lighting is insufficient, and there is a glare hazard adjacent to the window. The performance of the target building has unquestionably increased following the repair of 12 measures, including the bay windows, exterior walls, and solar energy. The influence of strong winds in winter and tranquil winds in summer greatly decreased in terms of the wind environment. In the light environment, indoor lighting is more uniform; the range of (Universal Design index) UDI100–2000 increased from 9.2% to 32.7%; and UDI2000, which may cause glare, decreased by 28.4%. Energy savings and pollution reduction rates were as high as 19.8% and 38.8%, respectively, due to the installation of solar photovoltaic panels. Based on all the measures, the overall energy saving rate of the target building was 63.8%, and the CO_2 emission reduction rate was 90.3%.

Keywords: severe cold area; existing buildings; physical environment; renovation; energy-saving; emission reduction

Citation: Liu, Y.; Chen, D.; Wang, J.; Dai, M. Energy-Saving and Ecological Renovation of Existing Urban Buildings in Severe Cold Areas: A Case Study. *Sustainability* **2023**, *15*, 12985. https://doi.org/10.3390/su151712985

Academic Editor: Dušan Katunský

Received: 25 June 2023
Revised: 10 August 2023
Accepted: 22 August 2023
Published: 29 August 2023

1. Introduction

Due to the enormous effect on the climate, the link between architecture and energy use has become a key concern in recent years. The need for structures and infrastructure rises along with the expansion of metropolitan areas and the world's population, which results in increasing energy usage. A sizeable portion of the greenhouse gas emissions are caused by building construction and operation. The situation can be improved by taking measures in aspects such as building design, materials, heating and cooling systems, and energy-efficient technology [1,2]. Building energy consumption is an important part of global energy consumption, accounting for 32%, and building heating energy consumption accounts for 32–34% of the total energy consumption [3–5]. By 2020, China's total building area is 83.302 billion square meters, of which residential buildings are 60.356 billion square meters, including urban residential buildings, which are 27.842 billion square meters, and non-residential buildings, which are 22.946 billion square meters [6,7]. The energy consumption generated by construction activities accounts for 26.7% of the total energy consumption of the whole society [8–10]. Many existing buildings have issues such as high energy consumption, erratic carbon emission, poor environmental function, and other issues because early architectural design and construction standards were constrained by economic factors and construction technology [11–13]. As a result, many buildings still stand today with these issues. Therefore, it is crucial to carefully research eco-friendly renovations of existing structures in extremely cold regions [14,15].

Earlier research regarding the rehabilitation of structures has been conducted. The selected green building rating system standard was adopted by Suman et al. [16]; then, a new framework to determine the best renovation strategy of existing office buildings based on a cost–benefit analysis was developed, which provided early decision support for the sustainable renovation of office buildings. Kalamees et al. [17] constructed an energy efficiency model and an economic feasibility analysis model for residential renovation, which provided a reference for Estonian buildings to develop energy saving measures and renovation schemes. Inspired by this, the building renovation paradigm adopted in this study considers economic feasibility. Simple and economical ways of retrofitting old buildings are favoured. Assimakopoulos et al. [18] developed the simulation model of the building-factory system and examined the effects of the St. George's Palace industrial refurbishment on energy usage and the environment. In the last ten years, the research on building renewal has developed rapidly. Xu et al. [19] developed a new hybrid energy system of solar air collector + air source heat pump + energy storage, which is used for facilitating energy saving through ultra-low energy consumption in severe cold areas. The feasibility and performance of the hybrid energy system were studied in the Hailar region. Fu et al. [20] investigated the key technology from the external design, enclosure structure, and energy supply of energy-saving buildings by taking the Qiyi department store as an example. In comparison, this piece provides more measures and metrics used to save energy and reduce emissions, although it does not provide an in-depth discussion around these technologies. According to each stage of the super high-rise building life cycle, Fang et al. [21] established a super high-rise buildings impact evaluation system after thoroughly analyzing the impact of super high-rise buildings on the environment during the construction and operation management phases. Li et al. [22] designed the three-dimensional dimensionless energy saving index parameters of atrium office buildings in severe cold areas, which solved the contradiction between the flexibility and universality of atrium geometries that are not affected. Aiming at a new type of energy-saving building with concrete sandwich straw block houses, Jiang et al. [23] measured their cold consumption index and heating power consumption index through experiments and conducted experimental research on their thermal insulation performance and moisture performance. In addition, they also studied the energy-saving effect of the external thermal insulation wall of prefabricated residences in hot summer and cold winter areas [24]. In the research of this paper, it was found that the measure of "installing light-blocking mirrors" also has a significant effect on energy saving and emission reduction, which is a supplement to previous research. Xu et al. [25] established an optimization model of existing building renovations using the outdoor average universal thermal climate index (UTCI) as the performance index to evaluate urban microclimates. At present, the evaluation indexes of energy consumption are mostly included in the green building evaluation standards and energy-saving design specifications.

With the passage of time, existing buildings will face the problems of structural deterioration, functional obsolescence, and high energy consumption. In this paper, a high-rise residential building in a severe cold region was selected and its wind, light, thermal, and energy consumption environments were simulated using Phoenics, Ecotect and Design Builder software. The basic performance of the building was diagnosed and analyzed. In order to achieve reductions in energy consumption and CO_2 emissions, form strategies (outdoor wind environment and indoor lighting), structural strategies (façade and roof), system strategies (heating, water supply and power supply, etc.), and equipment strategies (light fixtures, awnings, wind deflectors, etc.) have been adopted in the targeted weak areas. A prediction of the energy saving and emission reduction rate of the retrofitted building was made.

The common perception is that saving energy and improving energy utilization is always the key to energy efficiency in building systems. At the same time, renewable energy is the leading direction of energy consumption development.

The characteristic that can be identified is that most of the current green building evaluation standards and energy efficiency design codes include evaluation indicators for energy consumption, and these focus on assessment from the design perspective, while less assessment is made for existing buildings and buildings in the use phase. This study attempts to contribute in this area by proposing energy efficient and emission reduction retrofit solutions for a given sample of in-use buildings.

Another point is that in existing research on buildings and the environment, monitoring and diagnostics are mainly focused on the control aspects, and diagnostics are generally carried out using neural networks or fuzzy control and computer simulation to achieve diagnostic functions, with less research on failure diagnosis and runtime optimization. The failure diagnosis methods used in this study follow a certain logical structure system, and the architectural optimization approach forms an effective matching combination, which supplements the available data and information for the above two aspects. Compared with most of the existing studies that focus on the theoretical level, this study is closer to practice, and can provide a reusable and imitable evaluation system and retrofit methodology for the optimization of the ecological environment of buildings for more high-rise building retrofits in similar environments. The limitation is that more samples and cases are needed to confirm the applicability of the results of this study.

2. Materials and Methods

Chennengxi Tree Garden Community was built in 2002, located at No. 117 Haxi Street, Nangang District, Harbin City, Heilongjiang Province. Winters in the area are lengthy and bitterly cold. The average temperature in January is about 19 degrees below zero, and the heating time is up to 6 months [26–28]. The residential group consists of six point-type high-rise residential buildings, one small high-rise slab residential building, and supporting public buildings. The reconstructed building No. 4 is a point-type high-rise residential building located on the windward side of summer, with a butterfly-shaped plane and four households in one staircase. The interior is divided into two permeable households and two sunny households, both of which comprise three rooms and one hall. The interior is small, with a great depth and one side of lighting, which is not conducive to natural lighting and ventilation, as shown in Figure 1. The most prominent feature of the target building is that there are bay windows in four directions, which increases the building surface area and heat loss.

Figure 1. Photos of existing buildings.

For the renovation of the targeted building, the methods are as follows: (1) Primary wind, light, and thermal energy consumption environments are included in the basic performance diagnosis of the target building. Phoenics software is used to simulate the wind field at 1.5 m elevation of the target building throughout several seasons as part of the wind environment diagnostic. Outdoor wind speed, wind pressure differential, indoor air age, and surface wind speed are the primary evaluating factors. With DF (Daylight Factor), DA (Daylight Area), UDI, and DAmax as evaluation criteria, Ecotect software was selected to diagnose the overall light environment in the building. Through the Design Builder software, the operation energy consumption and operation carbon emissions of the target building are calculated after the parameters, such as shape coefficient, external wall structure, and window–wall ratio, are input. (2) Aiming at the high energy consumption area of the building, the renovation design is carried out from four aspects: strategy, structure strategy, system strategy, and equipment strategy. This paper proposes 12 measures, such as removing bay windows, local overhead, installing wind deflectors and solar energy utilization, dredging outdoor wind environment, optimizing indoor thermal environment, improving indoor light environment, and introducing sustainable energy utilization, to comprehensively optimize existing building performance. (3) The rate of energy savings and CO_2 emission reduction that can be achieved after a building renovation is predicted by comparing the physical environment changes before and after the renovation, combined with the single target sensitivity analysis of various measures.

3. Results and Discussion

As a result of the increased wind pressure on the windward side of the structure, unfavorable circumstances, including top gradient wind, bottom corner wind, and narrow pipe flow, will develop. In order to demonstrate the wind environment field, light environment field, and thermal energy consumption field one by one [29,30], it is essential to diagnose the performance of the target building.

Wind environment. Chennengxi Tree Garden Community is designed as an enclosed layout of a high-rise group. In winter, the wind speed is about 2.6–6.0 m/s near the 1.5 m elevation of the ground, especially in the active site surrounded by buildings. The wind speed in many places is more than 5.5 m/s and the wind amplification factor is 1.5 (6/4). Although the building is not at the windward position, the wind pressure difference between the windward side and the leeward side in the winter is still large, at about 10–26 Pa. In summer, the target building is located on the windward side, the outdoor wind speed is 1.5–2.3 m/s at 1.5 m elevation, the area of static wind area is small, and the wind pressure difference on the building surface is 2.6–4.8 Pa, which is conducive to the formation of natural ventilation inside the building. At the height of 16th floor in summer, the air age of the indoor main space is 0–320 s, and the ventilation condition is good, which is conducive to health. However, the problem of surface wind speed is serious in winter and the local wind speed at the upper windward side is 4.8–6.0 m/s, which leads to excessive inlet wind speed in the appropriate ventilation period in winter, as shown in the combined information reflected in Figure 2.

Light environment. The point-type envelope of the building of Chennengxi Tree Cultivate Community is more likely to meet the lighting conditions beneath the building partition. Hence, the daylight time of all the floors of the target building on a cold day is more prominent than 2 h. A recreation of the indoor light environment is shown in Figure 3. In which, DF denotes that the lighting coefficient of 53% is more prominent than 2%, and the normal brightening is 4.14%. DA indicates that all the measurements within the unit plane are within 0–94%. In total, 51% of all the measurements reached DAmax over 5%. Within the indoor light environment recreation, it can be seen that the inside lighting is insufficient, and glare across the window is apparent. In this manner, the room facing south is chosen for a point-by-point examination. The chosen room measured 3500 mm × 5600 mm, and the inlet window estimate was 1800 mm × 2100 mm × 600 mm. The recreation appears in Figure 4. The lighting coefficient of 28% of the measurement is greater than 2%, and the normal brightening is 2.09%. All measurements within the unit plane are 65–93%. UDI100 is 24%, UDI100–2000 is 9%, and UDI > 2000 is 66%. The narrow windows play a part in self-shading, amplifying the indoor light and causing dimness within the deep window, and glare near the window is apparent causing the comfortable light environment dispersion zone to shrink.

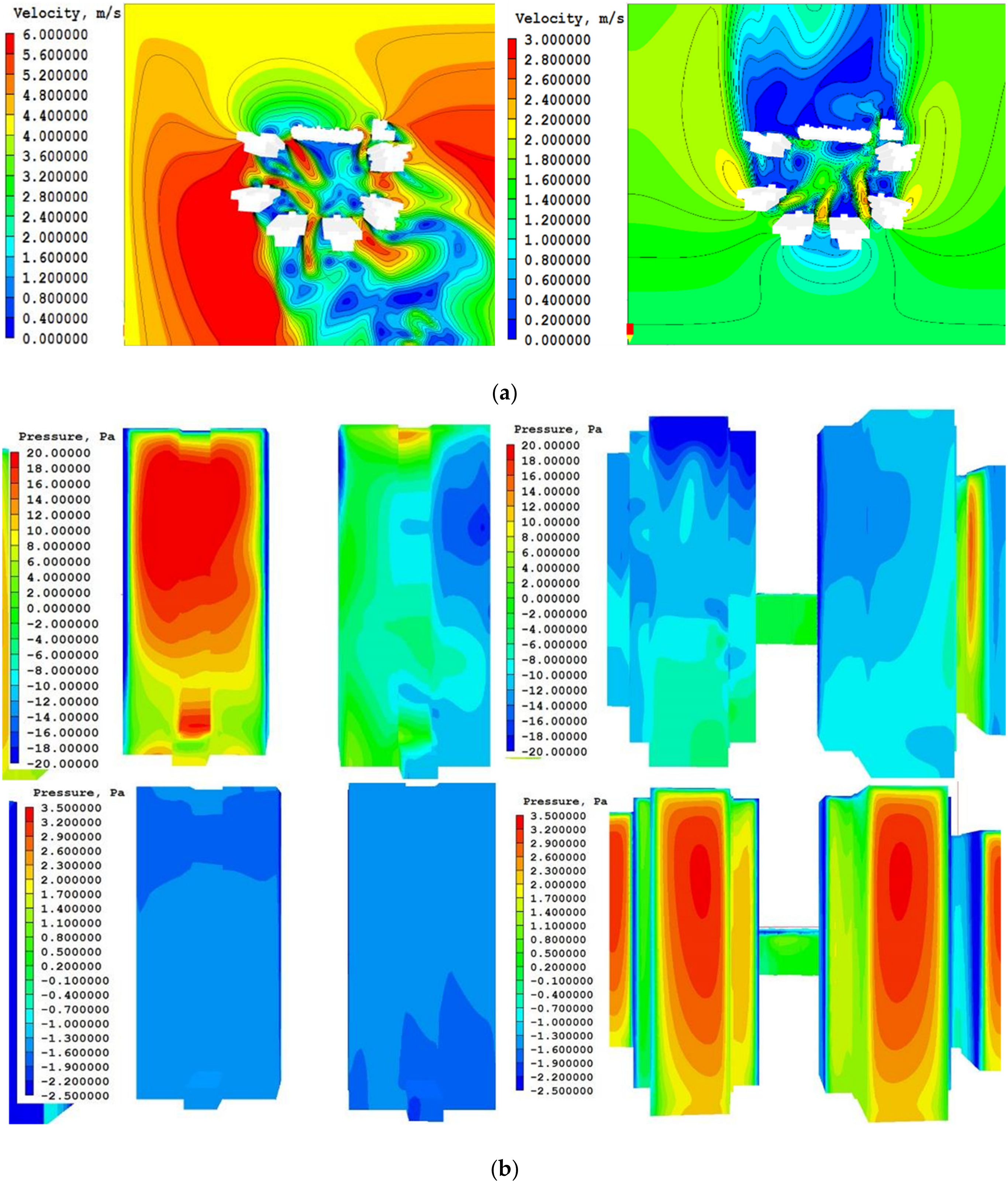

Figure 2. (**a**). Wind velocity of the measuring building area in summer and winter. (**b**). Wind pressure of the measuring building area in summer and winter.

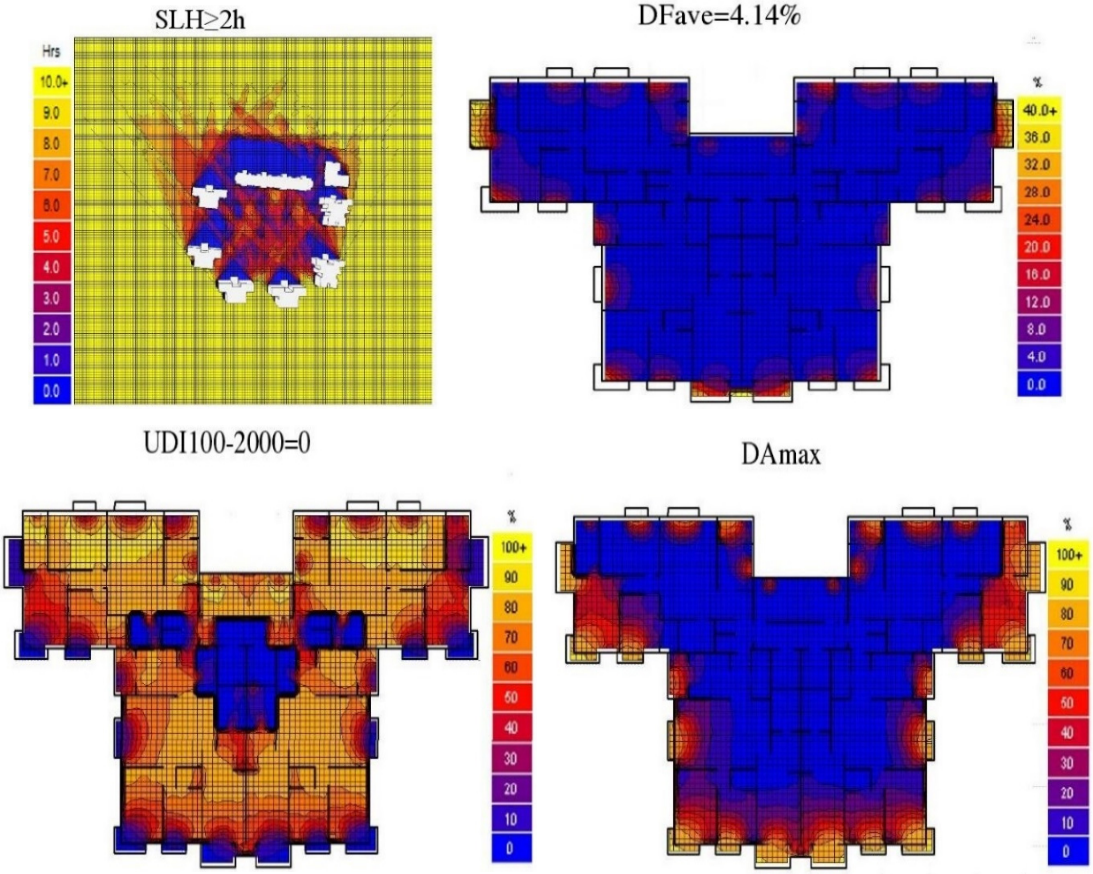

Figure 3. Diagnostic chart of indoor light environment.

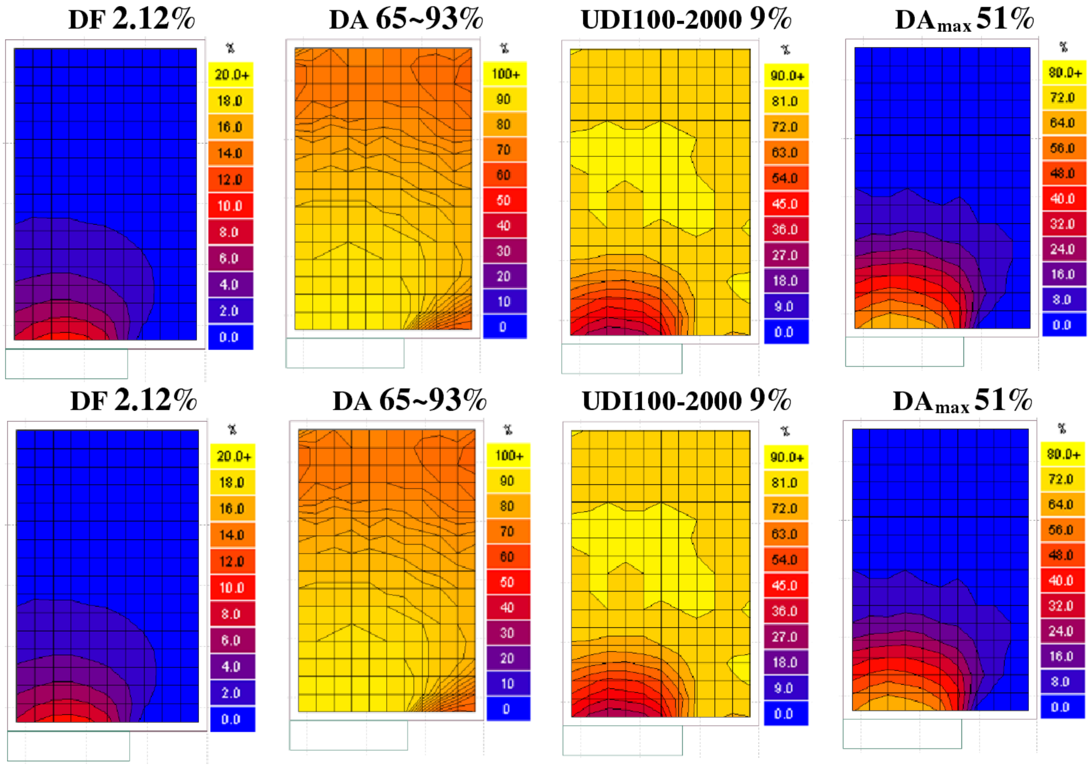

Figure 4. Diagnostic chart of light environment in south bedroom.

Thermal and energy consumption environment. Although the building has received alterations to some extent, No. 4 Chennengxi Tree Garden Community was originally built more than 20 years ago. The design parameters, such as shape coefficient, external wall structure, and window–wall ratio, were not significantly different from those of the standard building. The operation energy consumption and carbon emissions of the target building were 85.26 kWh/m^2·a and 46.31 kg/m^3·a, respectively, which were only 17% and 8.1% higher than those of the standard building, as shown in Table 1. Therefore, the space for reducing energy consumption and CO_2 emissions from the structural aspect is relatively small, and it is expected that the green renovation design of the target building will be mainly improved through a system strategy.

Table 1. Diagnostic table of thermal performance.

Building Parameters	Actual Building		Standard Building
Figure coefficient	0.27		0.26
Exterior wall structure	Reinforced concrete, 200 mm; EPS insulation board, 50 mm; U-value = 0.642 W/m^2·k		Reinforced concrete, 200 mm; EPSinsulation board, 50 mm; U-value = 0.642 W/m^2·k
Roof structure	Reinforced concrete roof, 120 mm; XPSinsulation board, 50 mm; U-value = 0.588 W/m^2·k		Reinforced concrete roof, 120 mm; XPSinsulation board, 130 mm; U-value = 0.247 W/m^2·k
Hall structure	Double glass curtain (6/l3 mm); U-value = 2.665 W/m^2·k		Double glass curtain (6/l3 mm); U-value = 1.786 W/m^2·k
Outer window	Double glass curtain (6/13 mm); U-value = 2.665 W/m^2·k		Double glass curtain (6/13 mm); U-value = 1.786 W/m^2·k
Window–wall ratio	S	0.35	0.35 (0.3–0.7)
	N	0.26	0.26 (<0.4)
	E	0.2	0.20 (<0.45)
	W	0.2	0.20 (<0.45)
Operating energy consumption	85.26 kWh/m^2·a		70.76 kWh/m^2·a
Operating carbon emissions	46.31 kg/m^3·a		42.59 kg/m^3·a

Renovation design and prediction feedback. Chennengxi Tree Garden Community is located in Harbin City; the regional climate includes a long, cold winter and the heating time is long. Therefore, in the target building's energy consumption distribution, heating accounts for the highest proportion of energy consumption, which is 61.4%, followed by domestic hot water at 20.8%, lighting at 13.2%, and refrigeration at 4.6%. In the renovation measures, the problem of improving the bay window is first considered. The existence of the bay windows greatly increases the exterior area of the building, resulting in the shape coefficient exceeding the limit. At the same time, the local overhead method is used to dredge the outdoor wind environment in the design. Then, the door hall is added with the sunshade board and the wind deflector to optimize the indoor thermal environment and the wind environment. In addition, the performance of the existing building has been comprehensively optimized by strengthening the insulation performance of the enclosure structure, for example by replacing the outer window, and other structural strategies and systematic measures, such as sub-metering and sustainable energy utilization.

Formal strategy: The main goal of the formal strategy is to enhance the efficiency of the indoor lighting and optimize the impact of external wind conditions. In accordance with the design's shear walls, the eastern rooms of the target building were removed and transformed into semi-open spaces for activities, as part of the overall strategy. Significantly, this alteration was carried out while keeping the same number of households and without compromising the strength of load-bearing walls. Before and after the retrofit, a thorough examination of the building's wind conditions was carried out using Phoenix software. Figure 5 visually depicts the distribution of the resulting wind field. It is important to acknowledge that every building in the group has the ability to impact the microenvironment of the entire area. Modifications have been made to the overhead space to improve outdoor comfort. These modifications not only reduce the impact of winter winds, especially in regions with wind speeds of 5.6 m/s or higher, but also enhance the calmness of the wind conditions in areas designated for summer activities, where wind speeds are below 0.6 m/s.

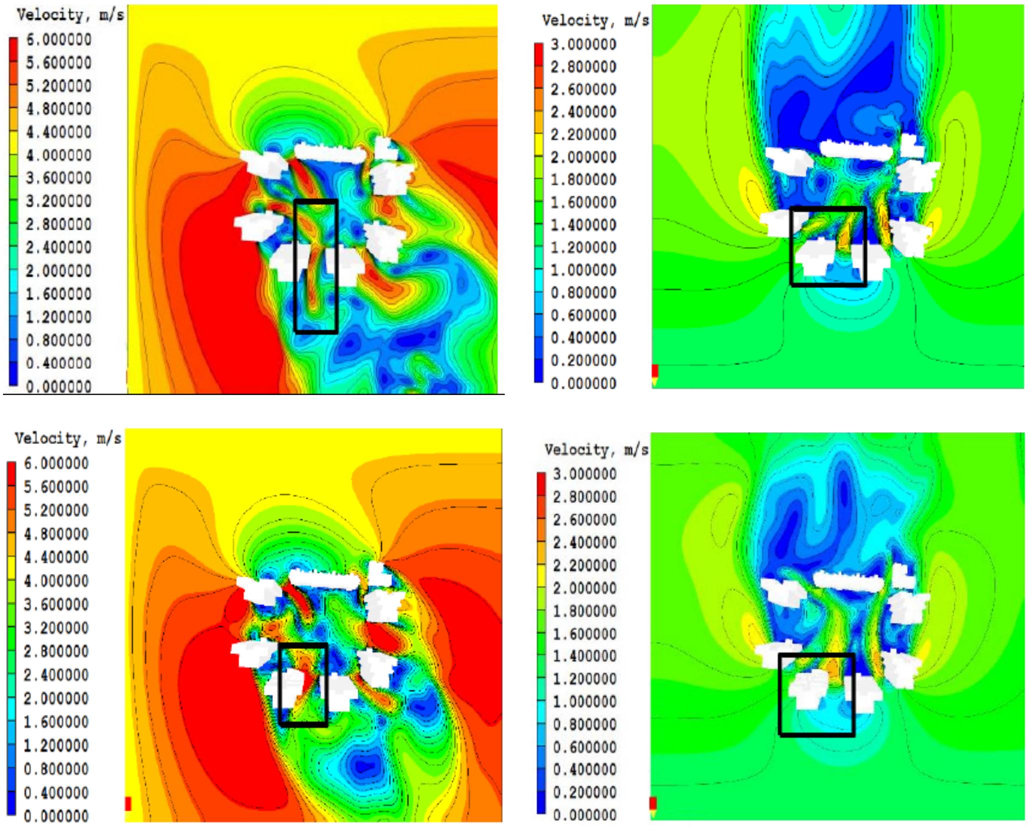

Figure 5. Comparison of outdoor wind environment before and after renovation.

To alleviate worries regarding the lack of transparency in the modeling process, the authors have provided additional details on particular elements of the retrofit strategy. One example is the detailed explanation of how the addition of PV panels, solar collectors, and other components affects energy usage and the subsequent emission of greenhouse gases. Extensive discussions have taken place to ensure transparency and reproducibility regarding the assumptions, simplifications, and considerations made by the model, including those related to factors such as the electricity mix employed.

The positioning of wind deflectors on the northern side of the building was carefully implemented to mitigate the higher wind speeds encountered on the upper portions of the building's exterior. Figure 6 illustrates five separate wind guide elements designed to lower surface wind velocities in the main functional zones on each level. Through the use of simulations, specific concerns were detected, as indicated by the highlighted portion in Figure 7. In the fifth simulated situation, precautions were implemented to limit the region exposed to high wind velocities to 3.2 m/s. A cleverly devised strategy for optimization was specifically directed towards important areas such as bathrooms and cooking spaces, leading to a highly effective approach.

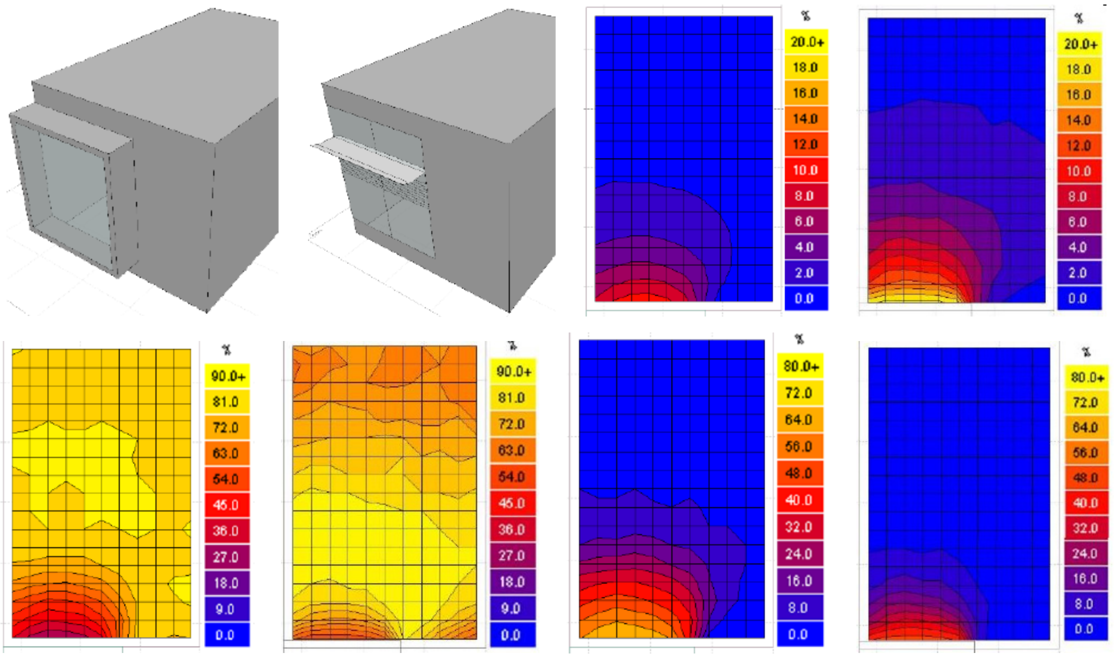

Figure 6. Comparison of light environment optimization of shading reflector.

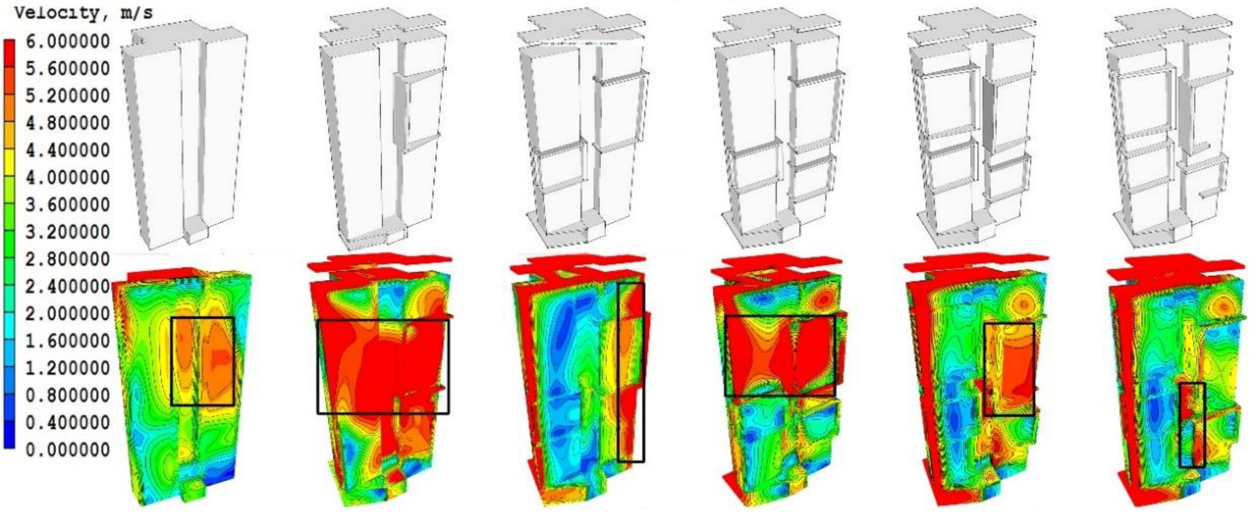

Figure 7. Design of wind deflector.

The authors used Ecotect software to simulate how the modified design affects indoor illumination in order to improve the lighting environment. The distribution of indoor lighting was enhanced by incorporating adjustable shading and reflective elements in place of the original bay windows. The shading structure was designed to effectively reduce the impact of direct sunlight in the summer months. Significant enhancements involved a significant boost of 23.5% in the UDI100–2000 range, a notable decrease of 28.4% in UDI2000 (which has the capability to produce glare), and a considerable reduction of 47.5% in the DAmax area (where illuminance exceeds 5%). In addition, the use of vertical greening on the mountainsides facing east and west has a double function, providing insulation in the summer and helping to decrease the need for cooling energy. To address issues with glare and enhance indoor lighting, shading elements and reflectors were installed on the southern side of the building, as shown in Figure 8. In an effort to reduce wind speeds on the upper parts of the building, wind deflectors and extra windshields were installed on the northern side.

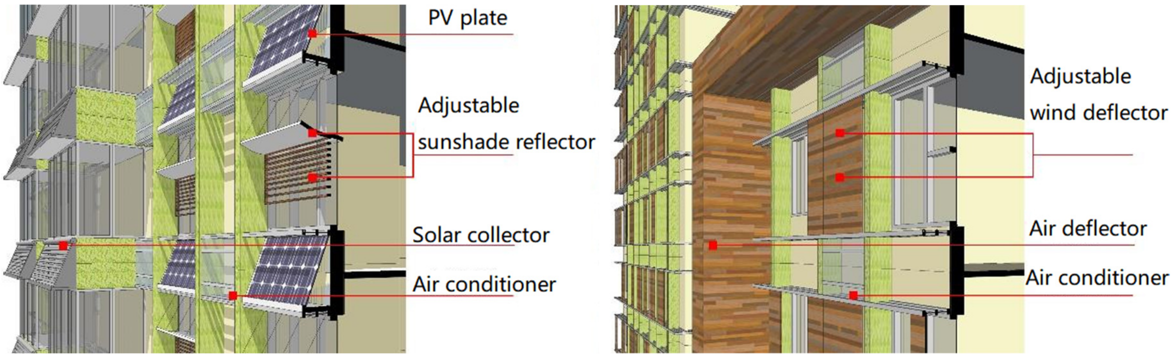

Figure 8. Renovation strategy of target building.

Effect on Carbon Emissions: A comprehensive analysis of the modification strategy's effect on carbon emissions has yielded noteworthy reductions. In a precise estimation, the implementation of shade reflectors is anticipated to yield a potential decrease of 7% in emissions, whereas the elimination of bay windows could potentially lead to a reduction of 4%.

Table 2 displays the energy-saving and CO_2 emission reduction performance attributed to several strategies. Each strategy has been meticulously outlined in terms of their respective associated measures, energy consumption values, energy-saving rates, and CO_2 emission reduction rates. The strategy labeled as "Comprehensive" exhibits notable advancements, achieving a noteworthy 63.8% decline in energy consumption and a 2.62% reduction in CO_2 emissions.

Table 2. Energy-saving and CO_2 emission reduction performance of different individual strategies.

Strategy	Measures	Energy Consumption	Energy-Saving Rate (%)	CO_2 ($kg/m^2 \cdot$Years)	Emission Reduction Rate (%)
Actual building		85.26		46	
Formal	Remove the bay window	77.2	9.5	44.15	4
	Local overhead	85.15	0.1	46.09	0.2
	Additional lobby	85.14	0.1	45.97	0.1
	Sunshade reflector	83.87	1.6	42.78	7.0
Construction	External wall insulation	81.38	4.5	45.34	1.4
	Roof insulation	84.72	0.5	45.91	0.2
	Outer window	81.23	4.7	45.05	2.1
System	Heating	79.26	7.8	44.81	2.6
	Solar collector	77	9.7	37.27	19.5
	Solar photovoltaic	68.38	19.8	28.15	38.8
Device	Energy-saving lighting	80.71	5.3	39.36	14.4
Comprehensive		31.57	63.8	2.62	90.3

Construction, system strategy, and equipment strategy. The target building has EPS and XPS insulation layers on the outer walls and roof, which have high thermal insulation performance but still fall short of the present specification's criteria. Therefore, in the renovation design, the external wall thermal insulation was thickened by 20 mm and the roof was thickened by 90 mm, so that the heat transfer coefficient of the external wall was reduced from 0.64 $W/m^2 \cdot K$ to 0.43 $W/m^2 \cdot K$, and the heat transfer coefficient of the roof was reduced to 0.25 $W/m^2 \cdot K$. The common double-layer glass (2.665 $W/m^2 \cdot K$) was replaced by double-layer LOE glass (1.786 $W/m^2 \cdot K$). The structure is identical to that of a typical building. The findings of the energy consumption simulation demonstrate that the structural approach contributes less to the reduction in emissions than the formal method. The emission reductions in the external wall reconstruction, roof reconstruction, and window replacement are 1.8%, 0.3%, and 2.6%, respectively. The system improvement strategy has achieved remarkable results, and the comparison of architectural modeling before and after the renovation is shown in Figure 9. Among these, the solar photovoltaic panels can effectively save energy by 20.4% and cause a reduction in emissions of 39.2%. Using the balcony to install 304.65 m^2 panels, the solar collector can supply all the energy for the domestic hot water energy consumption, which can effectively save energy of 9.8% and cause a reduction in emissions of 19.0%. In addition, in terms of equipment strategy, the emission reduction caused by LED lamp replacement is 145.2%.

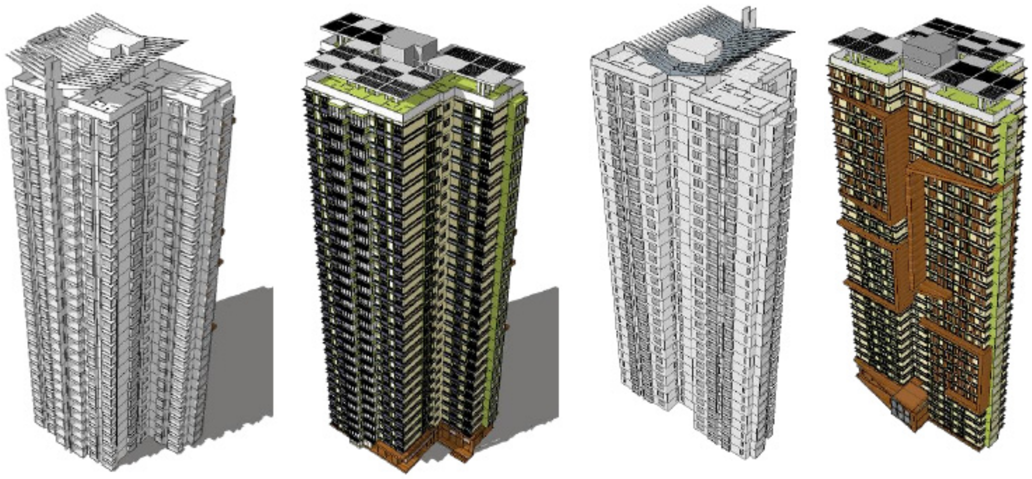

Figure 9. Comparison of architectural modeling before and after renovation.

Energy saving and emission reduction. The Design Builder software was used to simulate the energy consumption of 12 measures in the renovation and the standard formulae for each indicator are embedded in the software. The enhancement in energy saving and emission reduction performance, as well as the carbon emission and cost increment, are used to determine the sensitivity of the energy saving and emission reduction in various strategies, as shown in Table 2. In order to reduce emissions, the installation of solar photovoltaic panels is the most effective emission reduction measure, with energy saving rates and emission reduction rates as high as 19.8% and 38.8%, followed by solar collectors (9.7% and 19.5%), energy saving lamp replacement (5.3% and 14.4%), and shading reflectors (1.6% and 7%). Although the north wind deflector and local overhead strategy have little effect on carbon emissions, they are beneficial to the wind environment field in winter. Based on all the measures, the final energy saving rate of the reconstructed building is 63.8%, and the CO_2 emission reduction rate is 90.3%, with an obvious performance improvement effect.

4. Conclusions

Taking a high-rise residential building in a severe cold area as an example, the weak physical environment area was diagnosed. Green energy-saving measures were undertaken to renovate the building and the energy-saving and CO_2 emission reduction rate after the renovation were predicted. From the results of the building performance diagnosis, the wind speed at the corner of the building increased significantly, especially at the outdoor floor and top floor of the building, with local wind speeds of up to 5.8 m/s. There was a glare problem next to the window, and the inside lighting was overly dim. The area of DA_{max} in all the measuring points was as high as 51%. Operating energy consumption and carbon emissions were 85.26 kWh/m^2·a and 46.31 kg/m^3·a, respectively. From the aspects of form, structure, system, and equipment strategies, the ecological energy-saving of the buildings were implemented. In terms of wind environment, the strong wind area in the winter and quiet wind area in the summer decreased significantly. In terms of the light environment, the indoor lighting became more uniform, and the range of UDI100–2000 increased from 9.2% to 32.7%. UDI2000, which may cause glare, decreased by 28.4%. In terms of the thermal and energy consumption environments, the installation energy saving and emission reduction rates of solar photovoltaic panels were the highest, at 19.8% and 38.8%, respectively. By using DesignBuilder software to simulate the energy consumption of the target building, the final energy-saving rate of the reconstructed building was 63.8%, and the CO_2 emission reduction rate was 90.3%. Additional samples and cases are still required to support the method profile proposed in the research. This study offered a reusable and replicable evaluation system and retrofit methodology for optimizing the ecological environment of architectures under cold conditions.

Author Contributions: Conceptualization, Y.L. and D.C.; methodology, Y.L.; software, D.C.; validation, M.D., J.W. and Y.L.; formal analysis, J.W.; investigation, D.C.; resources, Y.L.; data curation, M.D.; writing—original draft preparation, M.D.; writing—review and editing, Y.L.; visualization, Y.L.; supervision, D.C.; project administration, D.C.; funding acquisition, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by Natural Science Research Funding Program for Colleges and Universities in Anhui Province (2022AH052435).

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

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest: The authors declared that they have no conflict of interest regarding this work.

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