A Study on Digital Governance of Historically Preserved Buildings Based on CFD and Thermal Imaging: The National Taiwan Museum of Fine Arts as an Example

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Abstract

This study sets out to improve the indoor and outdoor air environments of Historically Preserved Buildings through digital management, achieving energy savings and emission reduction. Historically, environmental control in art museums relied on manual aids and airtight construction, leading to significant energy consumption and complete Monument isolation. However, advancements in artificial intelligence have enabled the digital management of healthy environments.

This study utilizes a literature review, case studies, and computational fluid dynamics (CFD) . a literature review was conducted to collect data on active and passive Monuments, healthy art museum environments, and digital governance of Monument and environmental control. The National Taiwan Museum of Fine Arts (NTMA), Museums of Historical Preservation, was selected as the primary research target, and data was collected through field surveys, aerial photography, and construction of a three-dimensional model. wind environment simulation and thermography analysis were conducted through PHOENICS and PIX4D, and a proposal was made.

This study yielded the following two conclusions about NTMFA:1. Direct isolation of the physical environment control and aesthetics-oriented external planting methods make it difficult to reduce the indoor temperature and improve the air quality. These methods are also very energy-consuming；2. The NTMFA employs four strategies to enhance indoor and outdoor spaces, passive and active design, area redrawing, digital management of active design area, digital management of passive and active mixed area, and improvement of passive area. These strategies prevent direct isolation between the Monument and the environment while optimizing the indoor and outdoor wind environments.

1. Introduction

As global warming intensifies, the demand for comfortable living environments has spurred the widespread use of building equipment such as air conditioning. Meanwhile, architectural digital governance is increasingly relying on such equipment to create comfortable environments.However, comfort doesn’t guarantee health: respiratory disease spread and Sick Building Syndrome incidence underscores the ecological harm of environmental isolation for comfort. Additionally, escalating energy crises and environmental pollution from the extensive use of building equipment require academia and industry to revisit architectural digital governance through three critical dimensions: climate change, healthy environments, and energy security.

NTMFA is selected as the research object to explore feasible approaches to improving indoor and outdoor wind environments in public buildings through digital governance, aiming to achieve energy conservation and emission reduction while ensuring both artwork preservation and user comfort.Through a systematic literature review, this study analyzes core domains including active and passive architecture, healthy museum environments, and digital governance of building and environmental control, to establish a robust theoretical framework for subsequent research.

The research formulates three key questions: first, to investigate the reasons for the isolation of art museums' overall architectural space from the external environment; second, to examine whether isolated environments can effectively ensure users' health needs while providing comfort; and third,to explore constructing a healthy environmental system for art museums while ensuring art preservation and user comfort.A mixed-methods approach integrating qualitative and quantitative methodologies, including literature reviews, case studies of NTMFA, and simulation analysis, is employed to investigate the interactions between building design and its physical environment. The inquiry focuses on the relationships between active and passive design strategies and environmental parameters such as temperature, air quality, and wind speed.

This study has limitations: it focuses solely on the wind and thermal environments of NTMFA, excluding other physical factors; it examines only the relationships between the building’s active and passive design and parameters like temperature, air quality, and wind speed, with other design-environment associations beyond its scope. It is anticipated that this research will provide new perspectives for digital architectural governance in public buildings to foster healthier, energy-efficient, and sustainable environments.

2. Literature Review

The literature review in this study will be divided into three parts: the first part will focus on understanding active and passive buildings; the second part will explore healthy art museum environments; and the third part will investigate digital governance of buildings and environmental control.

2.1 Architecture for Active and Passive

Regarding the development of the relationship between architecture and its surrounding environment, L.H. Li (2015) believes that it includes two parallel threads. On the one hand, since Willis Carrier invented the air conditioner in 1902, there has been a rapid development of building equipment and machinery, and the paradigm of isolation and control between architecture and the environment has been continuously established. On the other hand, there is the continuous research on environmental design methods from the pre-modern period, which focus on climate design, solar energy, and other aspects.

L.M. Zhang (2022) defined these two parallel threads as active architecture and passive architecture respectively. Active architecture is defined as a design approach that utilizes mechanical systems (e.g., air conditioning, heating) to artificially regulate indoor environments.In contrast, passive architecture scarcely applies active devices when regulating the indoor temperature and humidity during the construction process. It makes full use of the high airtightness and thermal insulation properties of the building to meet the requirements of indoor heating, cooling and other environmental needs.Furthermore, X. Liu et al. (2015) believed that this passive design conforms to nature, and is also influenced and restricted by the regional environment, possessing obvious regional characteristics and climate adaptability.

This study posits that both active design and passive design are indispensable in architectural design. Passive design is capable of satisfying the heating and cooling requirements of the indoor environment for users without expending excessive energy. In scenarios where the comfort and well - being of occupants cannot be ensured without the implementation of active systems, active design strategies, through the orchestrated deployment of mechanical engineering interventions, can effectively optimize indoor thermal conditions, humidity levels, and air quality parameters, thereby establishing an environment that is both highly comfortable and conducive to physiological health.

2.2 The Creation of a Healthy Environment in Art Galleries

The creation of a healthy environment in an art museum demands comprehensive attention to both the preservation of artworks and the well - being of museum visitors. The primary pollutants in art museums include water vapor, carbon dioxide, other inorganic contaminants, volatile organic compounds (VOCs), and biological particles (Carletti, C. et al., 2020). The concentration of water vapor is related to relative humidity, which in turn affects the growth of mold. There are numerous species of VOCs in art museums, primarily originating from human metabolism, cleaning agents, paints, pesticides, adhesives, furniture, decorations, and building materials. The main biological particles found in art museums are dust mites, fungi, and bacteria.

From a professional perspective of artwork preservation, maintaining long-term high-quality air quality is of critical significance for the preservation of artworks, and three core conditions need to be met: 1. Eliminate pollution sources: Prevent and control harmful gases, and strictly prevent the intrusion of hazardous substances. 2. Environmental purification: Employ natural or artificial methods to reduce the generation of pollution sources. 3. Air purification and air-conditioning system treatment: Implement filtration measures and control the temperature and humidity. (Wang, P.Y., 2001). S.S. Chen (1999) pointed out that although the architecture of art museums affects the maintenance of ideal temperature and humidity, the air-conditioning system remains crucial for the preservation of collections.

From the perspective of human health, a significant number of museums employ air-conditioning systems as the primary ventilation method to maintain constant temperature and pressure, which leads to poor indoor air quality in such institutions. C. Carletti et al. (2020) conducted assessments of the indoor air quality in the Uffizi Gallery in Florence. The results demonstrate that prolonged enclosure and high crowd density in the venue have led to poor indoor air quality.The study points out that excessively high concentrations of air pollutants in art museums can not only affect human health but also potentially trigger diseases.

Ventilation is essential for reducing air pollutant concentrations. This study considers that there is a certain correlation between wind speed during ventilation and indoor user comfort. P.Y. Wang (2017) demonstrates that air velocity significantly influences indoor comfort, with distinct effects across different ranges: airflow is nearly imperceptible at less than 0.25 m/s; optimal and work-compatible at 0.25~0.5 m/s; generally acceptable but requiring caution for paper displacement at 0.5~1.0 m/s; noticeable wind discomfort at 1.0~1.5 m/s; strong airflow at 1.5~2.0 m/s causes significant agitation and heightened discomfort; and strict prevention of "draft" intrusion is required at >2.0 m/s due to severe comfort degradation. The study emphasizes the necessity of precisely regulating ventilation rates and optimizing airflow trajectories to balance pollutant reduction and thermal comfort, thereby ensuring work efficiency and maintaining a healthy indoor environment.

Wind Speed	Indoor User Perception
0.0~0.25m/s	Imperceptible
0.25~0.5m/s	Pleasant and non-disruptive to work
0.5~1.0m/s	Pleasant, but be careful of papers being blown away
1.0~1.5m/s	Slight wind impact and unpleasant blowing; thin paper on desks may be scattered
1.5~2.0m/s	Strong winds cause papers to fly around. Controlling air volume and flow paths maintains work efficiency and health
Above 2.0 m/s	Beware of draughts entering the room, causing discomfort to occupants.

Table 1. Indoor user comfort under different wind speeds

In conclusion, an art museum employ equipment to maintain constant temperature and humidity for collection preservation, while also considering indoor air quality, ventilation patterns, and thermal control to create a healthy indoor environment.

2.3 Digital Governance of Architectural and Environmental Control

In the study of the relationship between art museums and their environments, "isolation" is regarded as a key strategy. Architects employ technological means such as high-airtight building structures and space ventilation systems to achieve this separation, arguing that with technological advancement, this form of technical isolation has become an inevitable trend. However, thermal insulation technologies emerging from the modernist era are in contradiction with the first law of thermodynamics (Moe, K., 2010). Specifically, the isolated systems established by such isolation technologies are incapable of performing work during adiabatic cycles, thereby necessitating increased energy consumption for cooling processes. Additionally, the application of technology should return to a reasonable position, emphasizing that its development direction and usage patterns are more determined by human consciousness rather than technology itself (Green, B., 2019) .

Since the United Nations introduced the Sustainable Development Goals (SDGs) (The United Nations, 2015), there has been a growing global focus on health and environmental sustainability. Guided by this mindset, constructing harmonious and healthy environments has become of utmost importance. With the rapid advancement of artificial intelligence, this study argues that redefining the relationship between architecture and the environment through digital governance to create harmonious and healthy indoor-outdoor building environments has become an inevitable trend.

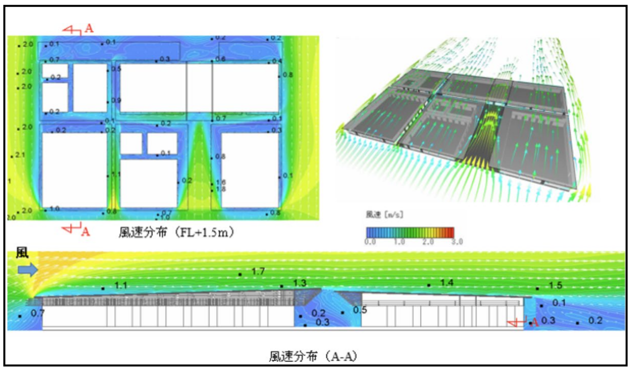


Figure 1. BIM Wind Speed Distribution Simulation Diagram for Tokyo Olympic Village Before Construction.

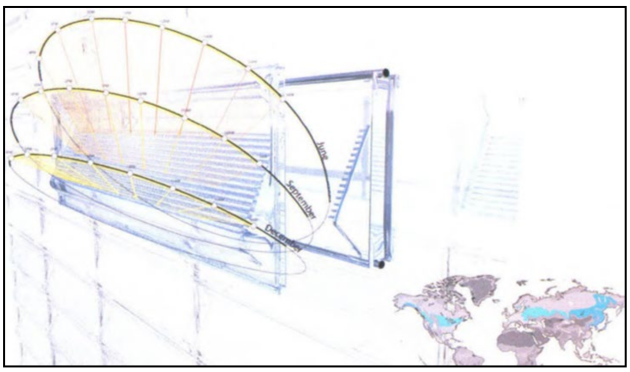


Figure 2. Research Diagram of High-Performance Terracotta Brick Interface Systems.

The athlete village of the Tokyo Olympic Village utilized BIM 3D models for environmental analysis before construction (Figure 1), effectively reducing high-energy-consuming behaviors in physical environment control after the building was completed (Nikken Sekkei., 2020). Meanwhile, a study has proposed that through environmental parametric design methods, bioclimatic energy flows related to light, humidity, temperature, and energy gradients can be converted into data and regarded as environmental resources with development potential, thereby promoting the flow and recombination of the physical environment in architectural spaces (VOLLEN, J.O., 2015). The study further takes light as a parameter to design a building glass interface that can automatically adjust its angle over time Figure 2).

3. Physical Environmental Simulation and Analysis

This study employs on-site aerial survey for data collection, and utilizes PHOENICS and PIX4D for CFD simulation and thermal imaging analysis.

3.1 Case Introduction

NTMA was established in the 1980s and is located in Taichung City. As an important national art institution in Taiwan, NTMA houses a substantial collection of valuable artworks with significant historical importance. These collections encompass a wide range of fields, including traditional painting, sculpture, printmaking, photography, crafts, and contemporary art. Among them are masterpieces by early prominent Taiwanese artists, as well as creations of historical and commemorative significance. These precious cultural artifacts and artworks not only serve as essential resources for academic research, but also bear the mission of preserving and passing down Taiwan's cultural heritage. Therefore, NTMA plays a crucial and irreplaceable role in promoting art exhibitions, educational outreach, and cultural preservation, contributing profoundly to the continuity and advancement of historical culture.

The main building faces east-west, with core spaces including 15 exhibition halls, three educational spaces, an art street, an immersive technology application laboratory, a VR gallery, leisure areas, and an outdoor park displaying sculptures (Figure 3).Among these, exhibition spaces typically adopt active design due to the requirement for constant temperature and humidity to preserve collections. In contrast, visiting and educational spaces are designed to switch between active and passive modes, while outdoor activity areas employ fully passive design. Therefore, the museum aligns with this study's exploration of active and passive architecture.

Figure 3. Aerial View of NTMFA.

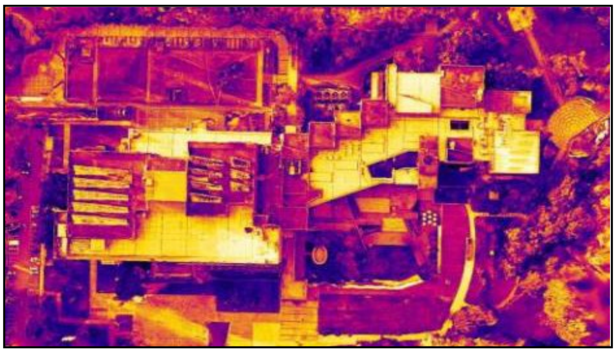


Figure 4. Point Cloud Analysis Diagram of NTMFA.

Notably, in its spatial design, NTMFA isolates internal building spaces from the external environment through active design. As shown in Figure 4, the point cloud map reveals that the museum's exterior appears light red, indicating a high-temperature zone. This suggests that the landscaping in outdoor spaces prioritizes aesthetic functions, failing to meet the demand for pre-entry body cooling of users and providing no substantial assistance in regulating indoor temperatures.

3.2 Model Construction and Condition Configuration

This study employs an aerial drone to conduct aerial photography of NTMFA, generating a scanned model of the building's volume (Figure 5). Precise dimensional data are obtained through measurement, and the architectural model is constructed using Sketchup modeling software (Figure 6). Subsequently, CFD wind environment simulation is performed via PHOENICS to derive accurate data and results.

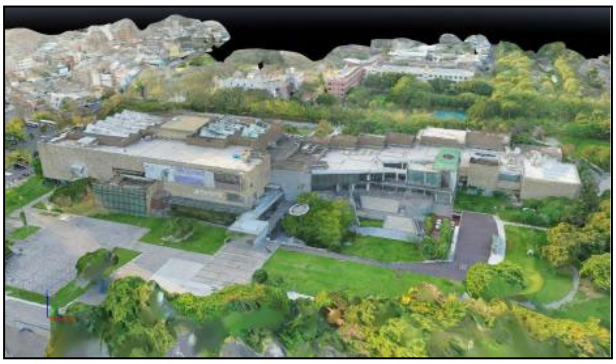


Figure 5. Scanned Model Diagram of NTMFA.

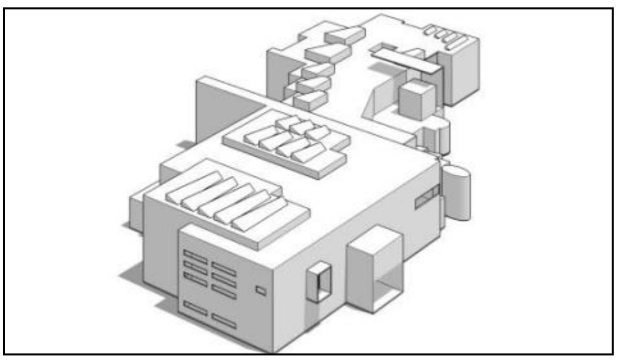
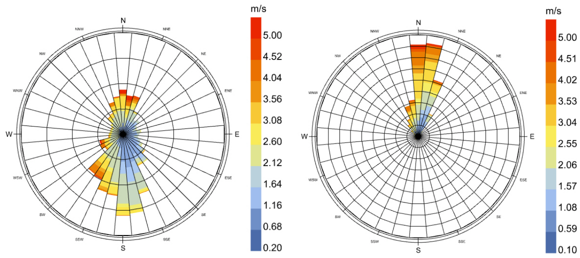


Figure 6. Sketch Up Model of NTMFA.

Based on the meteorological parameters of the West District in Taichung City, this wind environment simulation specifies the dominant summer wind direction as south with an average wind speed of 3.08 m/s and the dominant winter wind direction as north with an average wind speed of 5.00 m/s (Figures 7). The study uses these values to determine boundary conditions, adopting a gradient-distributed wind speed for near-ground velocities as the computational inlet condition (Central Weather Administration, 2022).



(a)Summer (b)Winter

Figure 7. Winter and Summer Monsoon Rose Diagram

4. Analysis and Discussion

This study uses CFD simulation technology to obtain wind speed maps of the first and second floors of NTMFA in winter and summer.Through comparative analysis, strategies to improve the indoor and outdoor wind environment of buildings via digital governance are proposed.

4.1 Analysis of Indoor Wind Speeds in Winter and Summer

Under the assumption that NTMFA operates without air conditioning and with all windows fully open, most areas on the first floor at a height of 1.5 meters above the ground exhibit wind speeds between 0.0 m/s and 0.25 m/s in both winter and summer, indicating a windless or excessively low wind speed condition; a small portion of areas have wind speeds distributed between 0.25 m/s and 1.0 m/s, falling within a relatively healthy and comfortable wind speed range; and only a negligible portion of areas experience wind speeds exceeding 1.0 m/s, representing excessively strong wind conditions (Figures 8 and 9).

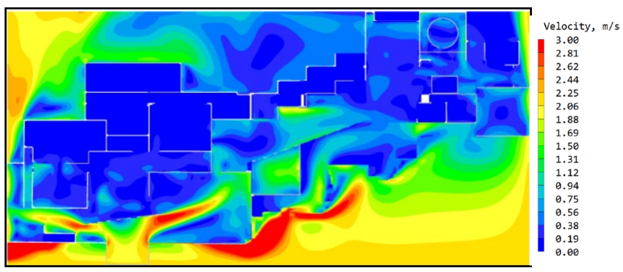


Figure 8. Wind Speed Diagram at 1.5m Above Ground on the Ground Floor in Summer

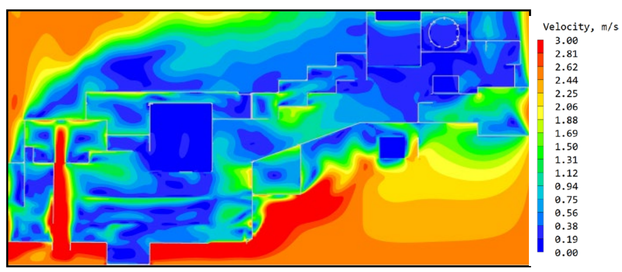


Figure 9. Wind Speed Diagram at 1.5m Above Ground on the Ground Floor in winter.

From the winter and summer wind speed maps at a height of 6.5 meters above the ground, it can be observed that under the assumption that NTMFA is operated without air conditioning and with all windows fully open, nearly half of the areas on the second floor exhibit wind speeds ranging between 0.25 m/s and 1.0 m/s due to the open skylights, indicating a relatively healthy and comfortable wind environment; the other half of the areas have wind speeds between 0.0 m/s and 0.25 m/s, representing a windless or excessively low wind speed condition; a negligible portion of areas perpendicular to the summer wind direction experience wind speeds exceeding 1.0 m/s, suggesting excessively strong wind conditions (Figures 10 and 11).

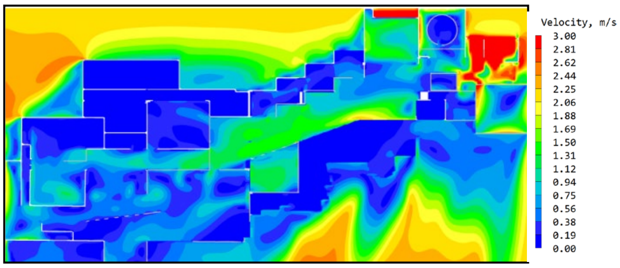


Figure 10. Wind Speed Diagram at 6.5m Above Ground on the Second Floor in Summer.

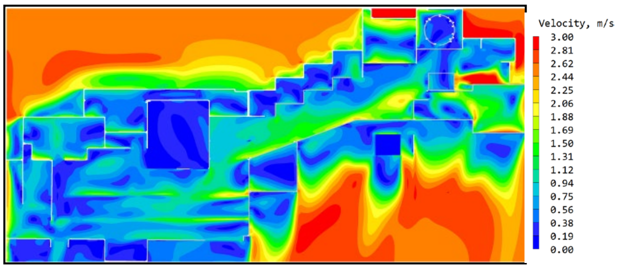


Figure 11. Wind Speed Diagram at 6.5m Above Ground on the Second Floor in winter.

4.2 Wind Environment Improvement and Digital Governance

Based on systematic data collection and analysis, this study proposes the following four dimensions for optimizing NTMFA:

4.2.1 Redesign of Passive and Active Design Zones: The current spatial zoning of the art museum adopts active design with air-conditioning and airtight components for all indoor spaces, while outdoor areas use passive design via vegetation. This approach severely dissociates indoor and outdoor environments, causing poor air quality in exhibition spaces and excessive energy consumption.This study recommends rezoning the passive and active design areas. The exhibition spaces should maintain active design to ensure a constant temperature and humidity environment. The sightseeing and educational spaces should be designated as hybrid zones combining both passive and active design elements. The outdoor spaces should retain the passive design approach (Figures 12).

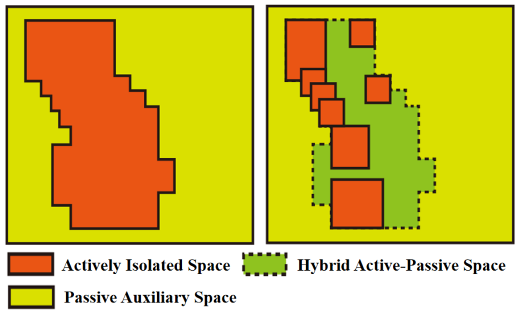


Figure 12. Redesignated Passive-Active Design Areas.

4.2.2 Digital Governance of Active Design Zones: Install air quality and temperature monitoring devices in active design zones. Automatically increase ventilation when air quality fails to meet standards, and use temperature distribution data to enable localized air supply by air conditioning systems, ensuring constant indoor temperature while reducing energy consumption (Figure 13).

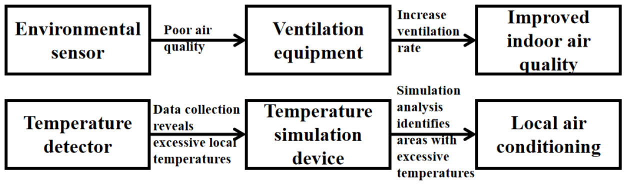


Figure 13. Digital Governance Flowchart for Active Design Areas.

4.2.3 Digital Governance Scheme for Passive-Active Hybrid Zones: In passive-active hybrid zones, indoor temperature monitoring devices and physical environment simulation equipment should be installed. The second-floor spaces shall dynamically adjust window opening modes and positions based on real-time wind direction and speed data. Meanwhile, artificial intelligence technology is employed to collect precise wind speed and temperature data .Through analysis by the physical environment simulation system, intelligent regulation is performed on the opening parameters of building doors and windows and the start-stop of air conditioning systems. This scheme ensures occupants' thermal comfort and reduces building energy consumption (Figure 14).

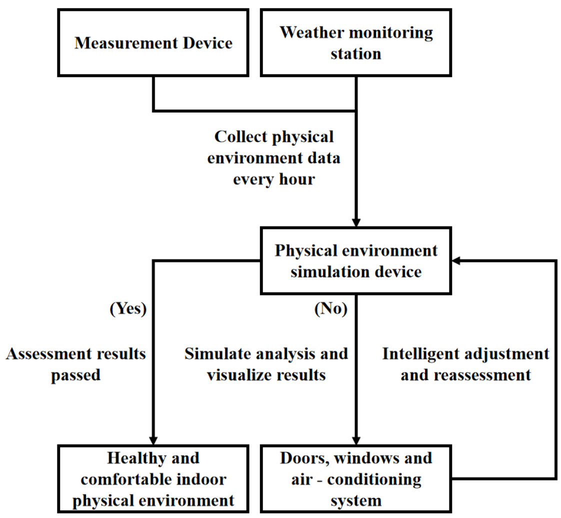


Figure 14. Digital Governance Flowchart for Hybrid Passive and Active Zones.

4.2.4 Enhancements for Passive Zones: Measures include adjusting the planting positions of outdoor trees to guide natural wind into building interiors, where tree canopies reduce wind temperature and optimize the air quality of incoming airflow.Additionally, greenery at building entrances effectively reduces visitors' surface temperature on entry, minimizing heat disturbances to indoor temperature and avoiding discomfort due to significant temperature gradients..

5. Conclusion

This study draws the following two conclusions regarding NTMFA:

5.1.1 Deficiencies in the Current Situation: The physical environmental control approach with direct isolation, coupled with the aesthetically - driven external plant cultivation, gives rise to challenges in indoor temperature reduction, subpar air quality, and significant energy consumption.

5.1.2 Strategies for Indoor and Outdoor Space Improvement: The indoor and outdoor environments of NTMFA can be enhanced via four methods: rezoning passive and active design zones, implementing digital governance in active design areas, applying digital governance in mixed passive - active zones, and upgrading passive areas. These strategies are intended to prevent the direct disconnection between the building and its surroundings while optimizing the indoor and outdoor wind conditions.

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