Numerical Simulation and Field Survey on Indoor Thermal Comfort for Healthy Building: A Case study on Lingnan Residential Building

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ABSTRACT

Due to COVID-19, people spend more and more time indoors. Healthy buildings, therefore, become more attractive to people than ever before. By summarizing specific requirements on relevant standards for healthy indoor thermal condition, this paper adopts numerical simulation and field survey to study indoor thermal comfort with a Lingnan residential building as a study case. After optimizing by building design strategy, the research results show that (1) The numerical simulation method can evaluate the indoor thermal environment, comparing the results from the field survey. (2) The study case did not meet the healthy indoor thermal environment requirements under natural ventilation. (3) By adding sunshades on windows, optimization measure is worked for healthy indoor thermal comfort. (4) Numerical simulation is used for predicting in advance. It helps the designers to solve practical problems.

INTRODUCTION

Healthy building

Healthy building is much more important nowadays. More and more people become aware of this because of COVID-19. How to ensure healthy environments for users' health and comfortable is crucial and essential. From part of the literature review of the healthy building, the necessity of research will be more clearly revealed.

In 1981, the 14th International Union of Architects (UIA) Congress held in Warsaw, Poland, published a declaration to emphasize the relationship of Architecture, Man and Environment, aiming to promote healthy living environment "Z.T. Zhong, J.H. Ding, J.M. Meng. (2018)". In 1986, WHO implemented the Healthy Cities Project to drive substantial development for healthy living environment "Takano, Takehito. (2003)". In 1988, the first Healthy Buildings Conference was held in Stockholm. Up to now, the 17th Healthy Buildings conference is planning to open online in Oslo. In 1990, Building Research Establishment (BRE) published BREEAM, the first set of standards for assessing, rating and certifying building environment. To this day, it still contains a "Healthy and Well-being" chapter focusing on healthy building "BRE. (2016)". In 1992, the USA established the National Center for Lead-Safe Housing to solve housing-related health problems. In 1999, China National Engineering Research Center for Human Settlements (CNERCHS), joining hands with professionals in areas of Architecture, Physiology, Hygiene, Sociology and Psychology, initiated research on healthy residential buildings "Publisher. (2016)". In 2004, the first Forum of Theory and Practice on Healthy Housing held in Beijing, China "Publisher. (2004)". In 2006, Professor Hugh Barton from WHO and Marcus Grant published the Health Map developed from Dahlgren and Whitehead's model in 1991, explaining the circle effect in healthy environment "H. Barton, M. Grant. (2006)". In 2014, the International WELL Building Institute (IWBI) published the WELL standard for assessing healthy building based on the LEED standard, which is the first integral healthy building standard in the world "Y. X. Tao, Y. Zhu, U. Passe. (2020)". In 2016, Healthy Building Evaluating Standard T/ASC02 was published in China, emphasizing building healthy environment according to local conditions. Its latest version will be published soon in 2021 "P. Mao, J. Qi, Y. Tan, J. Li. (2017)". In 2020, WELL Health-Safety Rating was published by the Task Force on COVID-19. This helps buildings and organizations address the health, safety and wellbeing of their most valuable asset—people.
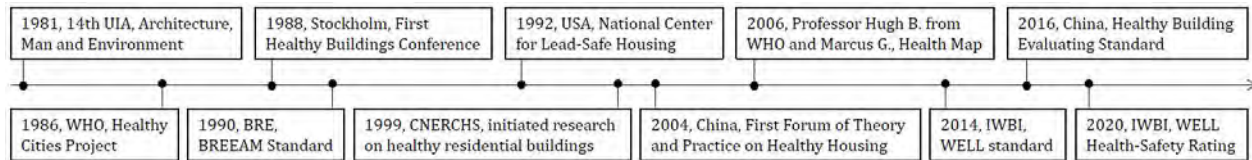
1981, 14th UIA, Architecture, Man and Environment	1988, Stockholm, First Healthy Buildings Conference	1992, USA, National Center for Lead-Safe Housing	2006, Professor Hugh B. from WHO and Marcus G., Health Map	2016, China, Healthy Building Evaluating Standard
1986, WHO, Healthy Cities Project	1990, BRE, BREEAM Standard	1999, CNERCHS, initiated research on healthy residential buildings	2004, China, First Forum of Theory and Practice on Healthy Housing	2014, IWBI, WELL standard	2020, IWBI, WELL Health-Safety Rating

Figure 1. Healthy building developing timeline

So the healthy building developed in the Architecture discipline at least 40 years until now (Fig. 1). It started from the international organizations, then developed in more and more countries, whether in academic, standard, practice or other aspects. China is focusing on this more than before, partly because it started at the end of the 1990s. But now China is developing fast. Moreover, affecting by COVID-19 is also one of the reasons. With the global and local focus on this, further research is needed.

Indoor thermal comfort

The thermal environment affects people's health all the time. In fact, most people spend almost 90% of their time indoors "D' Amico A, Pini A, Zazzini S, et al. (2021)". The indoor thermal environment is an indispensable part of a healthy building. Given this, research on indoor thermal comfort is required for the development of the healthy building.

Thermal comfort is one of the primary concerns during artificial climate design in a building and has a significant impact on health. In the 1920s, the term "thermal comfort" was generated to control the microclimate indoors "Karyono, K., Abdullah, B.M., Cotgrave, A.J., Bras, A. (2020)". In the 1930s, Thomas Bedford collected data of temperature, humidity, wind speed, and mean radiant temperature by questionnaires, reaching the conclusion that 18 ℃ is the most comfortable indoor temperature for factories in the UK. In 1966, ASHRAE started to use a 7-level thermal sensation standard which existed concurrently with the one proposed by Bedford in 1936. In 1970, Professor Fanger proposed Predicted Mean Vote (PMV) to evaluate the thermal sensation of people in the thermal environment "Fanger P O. (1970)". In 1973, Humphreys and Nicol put forward an adaptive model to improve human self-regulation in the thermal environment "Nicol JF, Humphreys MA. (1973)". In 1984, PMV became an international standard (ISO 7730). In 1992, an ASHARE 55 standard named Thermal Environmental Conditions for Human Occupancy published and had been renewed several times by 2017. In 1998, Brager and Dear further developed the adaptive model of thermal comfort "Brager GS, de Dear RJ. (1998)". In 2002, Peter Höppe researched different aspects for assessing indoor and outdoor thermal comfort "Peter Höppe. (2002)". In 2008, Hoof, J. van. investigated Fanger's PMV model for thermal comfort of all users "Hoof, J. van. (2008)". In 2011, Hassan et al. analyzed Tuskegee Healthy House by Visual DOE-4 software and field study "Hassan M A, Shebl S S, Ibrahim E A, et al. (2011)". In 2012, the Chinese standard Evaluation Standard for Indoor Thermal Environment in Civil Buildings published based on ISO 7730 and ASHARE 55 "GB/T 50785. (2012)". In 2013, Roudsari et al. used plugin Honeybee for Grasshopper to research the ASHRAE Adaptive Comfort Calculations to help designers create an environmentally-conscious design "Roudsari M S, Pak M. (2013)". In 2015, Croitoru et al. reviewed the most popular thermal comfort models and CFD methods of assessing thermal comfort in buildings and vehicular spaces "Croitoru C, Nastase I, Bode F, et al. (2015)". In 2018, Naboni et al. reviewed the simulation tools of CitySim Pro, ENVI-met, Autodesk Thermal CFD, Grasshopper plugins Honeybee/Ladybug from the designer perspective to compare the results of thermal comfort "Naboni E, Silvia C, Meloni M, Scartezzini J L, Ashrae. (2018)". In 2020, Farzaneh et al. researched the relationship between design variables with adaptive thermal comfort based on Ladybug and Honeybee environmental plugins. Results show how an enhanced design can significantly increase the thermal comfort in courtyard houses in a hot arid climate "F. Soflaei, M. Shokouhian, A. Tabadkani, et al. (2020)".

As shown in the above literature review, thermal comfort is essential to a healthy building as an architectural concept of almost 100 years of history. While being developed further with increasing maturity, these theories have been defined and incorporated into relevant standards. Moreover, the adaptive thermal comfort method is widely used under natural ventilation. The main methods for indoor thermal comfort research focus on field survey and software simulation. Now the critical issue is to use these mature theories and methods to solve practical problems. Here, an actual project located in China is used to do further research.

Research Framework

From the above introduction, this paper figured out the research framework (Fig. 2). Then, based on an actual project, the numerical simulation and field survey methods were used to evaluate the current situation, find out the problems and put forward the optimization design strategies to realize the comfortable indoor thermal environment for healthy building.
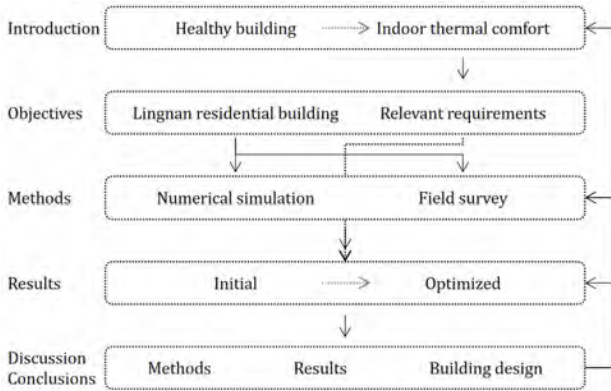
Figure 2. Research framework

OBJECTIVES

Lingnan residential building

The actual project for research is a standard layout of Lingnan residential building in Yuedao Residential Area (hereinafter referred to as Yuedao Courtyard), located in Jiangmen city, China. Yuedao Residential Area extends from north to south, with roads dividing it into different residential groups. Therefore it can be classified into 'neighbourhood', 'block', and 'single courtyard' by scale (Fig. 3). Moreover, the whole area is mirrored on the east and the west based on the standard layout of Yuedao Courtyard. The standard layout features two floors (Fig. 4) with a high courtyard wall. So the indoor thermal comfort is hardly affected by nearby buildings. This research focused on the entrance facing west Yuedao Courtyard. The standard building's results have universal in this situation.

Relevant requirements

Another objective is based on the Yuedao Courtyard and refers to the related requirements of healthy thermal comfort that should be observed in the research. Standards related to the healthy building include WELL and the Healthy Building Evaluating Standard T/ASC02, related to indoor thermal comfort include ISO 7730, ASHRAE 55 and GB/T 50785. Given the influence of the local environment, the Chinese standards T/ASC02 and GB/T 50785 are used in this paper. T/ASC02, which requires thermal comfort evaluation, follows GB/T 50785. Therefore, the relevant requirements in this paper are mainly derived from GB/T 50785, especially for the field survey. In fact, as mentioned above, GB/T 50785 is generated based on ISO 7730 and ASHARE 55. So the results of the study should show the same trend.

According to GB/T 50785, evaluation of indoor thermal environment should be conducted in main rooms or a single building. When evaluating a single building, at least 90% of its main rooms should meet relevant requirements before it can be regarded as reaching the corresponding level. There are three levels for the natural ventilation environment, as shown in Table 1. APMV refers to the "adaptive predicted mean vote" generated by optimizing PMV affected by the local environment. The equation is as below:

$$APMV = PMV/(1 + \lambda \cdot PMV) \qquad (1)$$

where:
APMV refers to adaptive predicted mean vote, *PMV* is predicted mean vote, and λ is the adaptive coefficient.

Figure 3. Yuedao Residential Area

For Yuedao Courtyard, λ is 0.21 according to GB/T 50785.

Figure 4. Yuedao Courtyard

This equation is for evaluation calculation. Relevant data can be simulated by software or measured by instruments, which will be introduced in the METHODS part.

Table 1. Evaluation levels of natural ventilation environment
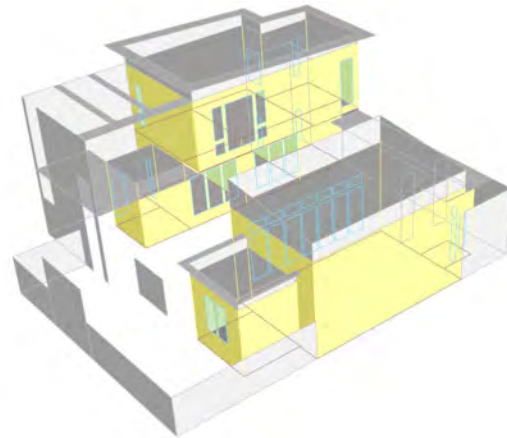
Level	Range
I	-0.5<=APMV<=0.5
II	-1<=APMV<-0.5 or 0.5<APMV<=1
III	APMV<-1 or APMV>1

Figure 5. Simulation model

METHODS

Numerical simulation

ASHRAE Adaptive Comfort of a whole year in Yuedao Courtyard was calculated via numerical simulation based on Rhinoceros software with Ladybug and Honeybee plugins. Ladybug imports standard EnergyPlus Weather files (.epw) into Grasshopper. The honeybee is an extension of Ladybug that increases the ability to work with EnergyPlus for calculating the adaptive thermal comfort "Lucarelli et al. (2020)". The simulation model showed in Figure 5 was built based on the standard building. The simulation condition was natural ventilation. After
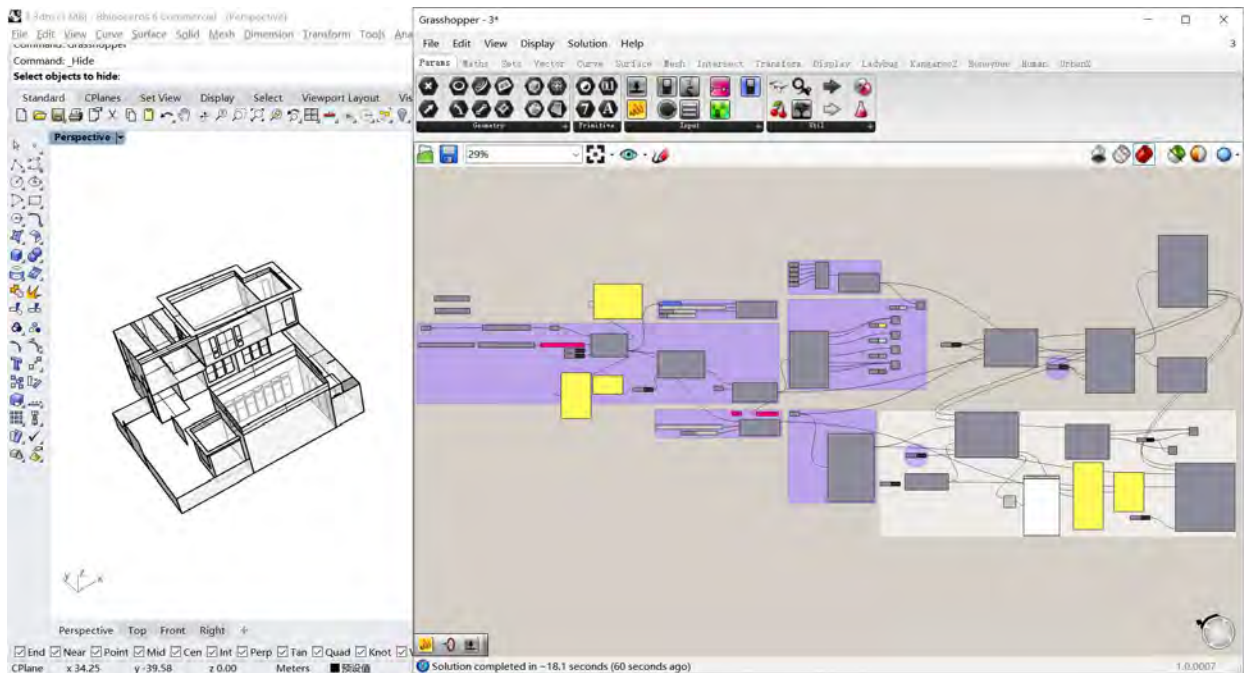

Figure 6. Simulation workflow

completing the workflow and setting up all the parameters, the calculation was started (Fig. 6).

Field survey

The field survey was conducted for 24 hours starting from 1:30 AM on July 18, 2019. The BX portable weather station was used to collect the data of outdoor air velocity (V), wind direction, atmospheric pressure (atm), air temperature (t_{out}), and humidity (RH_{out}). At the same time, TES-1341 anemometers and JTR04 black-bulb thermometers were used in 9 rooms to record indoor air temperature (t_{in}), humidity (RH_{in}), air velocity (V_a), and black globe temperature (t_g). According to *Standard of Test Methods for Thermal Environment of Building* JGJ/T 347, RH_{in} and t_g data were collected 0.6 metres above the ground, t_{in} and V_a data were collected 1.1 metres above the ground (Fig. 7 & Tab. 2).
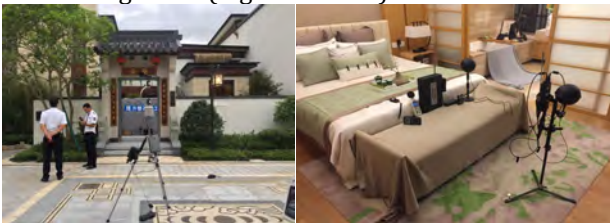

Figure 7. Outdoor and indoor field survey

Table 2. Instruments and parameters

Monitoring parameters	Instrument name	Instrument range	Instrument precision	Instrument photograph
v (m/s)	BX portable weather station	0~70.0m/s	±0.3m/s	
Wind direction (°)		0~360°	±1°	
atm (hPa)		10hPa~1100hPa	±0.1hPa	
t_{out} (°C)		-50°C~60°C	±0.3°C	
RH_{out} (%)		0~100%	±3%	
t_{in} (°C)	TES-1341 anemometers	-10°C~60°C	±0.1°C	
RH_{in} (%)		0~100%	±3%	
v_a (m/s)		0~30.0m/s	±0.01m/s	
t_g (°C)	JTR04 black-bulb thermometers	-20°C~125°C	±0.5°C	

RESULTS

Initial results

The numerical simulation results are shown in Table 3 and Figure 8. The comfort percentage of 10 rooms are no more than 50% of the whole year except for the No. 4&7 bathrooms. As shown in Fig. 4, these bathrooms all located in the corner of the building with small north-facing windows. So the indoor thermal comfort is better than the others. But all in all, Yuedao Courtyard should be optimized to solve the hot indoors problem. The comfort percentage of No.2 living room on the first floor and No. 8&9 bedroom with bathroom on the second floor is 48.48% and 24.32% separately. They are main rooms for receiving public or private living. And the second-worst indoor thermal environment is the cloakroom, and the comfort percentage is just 24.47%. These should be optimized for the user's health.

Table 3. Initial simulation results

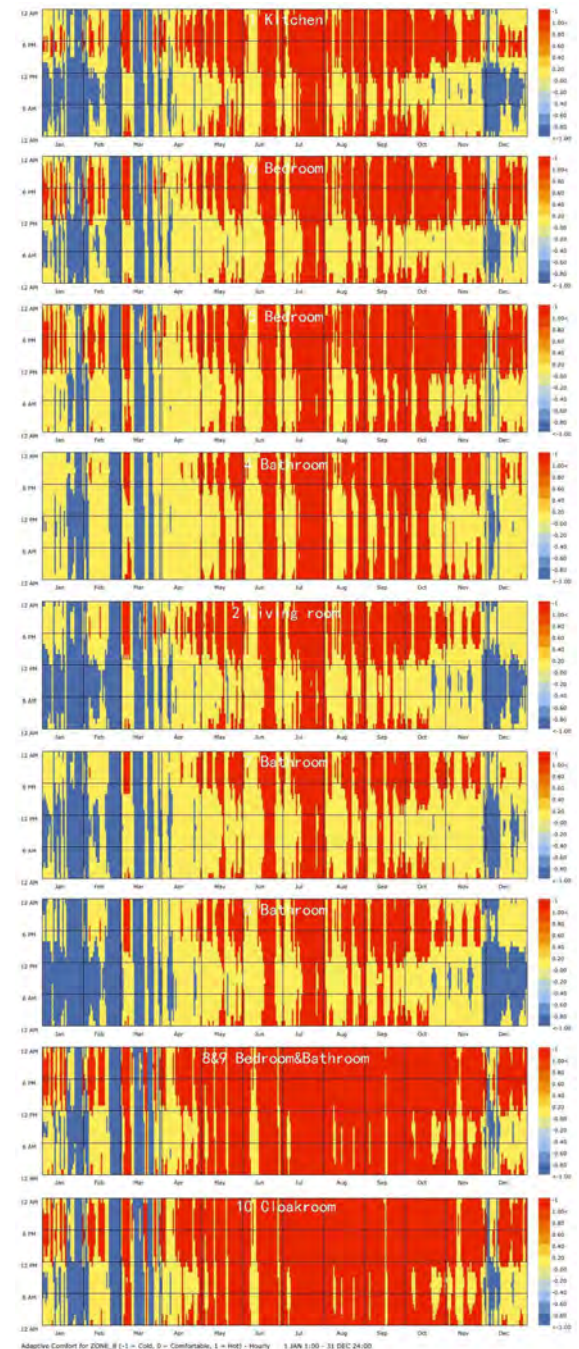| Room	1 Kitchen	2 Living room	3 Bathroom	4 Bathroom	5 Bedroom	6 Bedroom	7 Bathroom	8&9 Bedroom& Bathroom	10 Cloakroom
Comfort Percentage [%]	40.96	48.48	48.99	53.64	42.93	47.61	55.90	24.32	24.47

Figure 8. Initial simulation results chart

By field survey, the temperature data of outdoor and indoor were recorded, as shown in Figure 9. The BX portable weather station recorded a daily mean temperature of outdoor is 32.61 ℃ . The indoor temperature of the No.1 kitchen is higher than the outdoor temperature during 14:30-16:00. That because the window of the kitchen faced west, so the sunshine went into indoors directly. The indoor data was collected from 9 rooms to evaluate the adaptive thermal comfort. Due to a bit of operation error, the No. 4 bathroom data did not record successfully. However, that still meets the requirements according to GB/T 50785, which should evaluate at least 90% of the rooms. The result shows that the thermal comfort level of the measurement rooms is level III whatever for the single room or the whole building (Fig 10). Therefore, it is hot indoors that should be optimized.
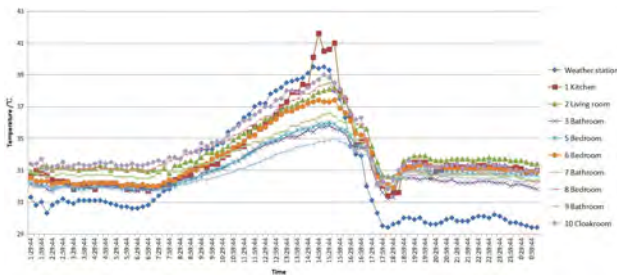

Figure 9. Outdoor and indoor temperature

Figure 10. Field survey results

Optimized results

Yuedao Courtyard (entrance faced west) indoor thermal environment is hot under nature ventilation from the numerical simulation and field survey evidence. But these buildings have been built, so how to solve the hot problem with as little as possible energy consumption is a question. Therefore, the passive design strategies were considering first.

Combining with the field survey, as shown in Figure 11, the building shading is not enough. Based on the local culture of the Lingnan building, the residential buildings always shaded by the eaves. Figure 12 shows an example of the Lingnan building with sunshades. So the optimization strategies combined with sunshades try to solve the problems and reflect the culture of local architecture characteristics.

The optimized model showed in Figure 13. Yuedao Courtyard mainly added the sunshades on windows of the kitchen, living room, bedroom and cloakroom, where the problems should be solved first that analyzed above.

After simulating, the optimized results showed that each room's hot indoors problem was solving to varying degrees. The compared simulation results of initial and optimized showed in Figure 14. The indoor thermal environment is optimized 25.78% in No. 8&9 bedroom with bathroom. Furthermore, the hot problem of kitchen and cloakroom is solved 17.57% and 20.80% respectively. The living room is facing north with big windows, so it is not optimized too much (9.76%).

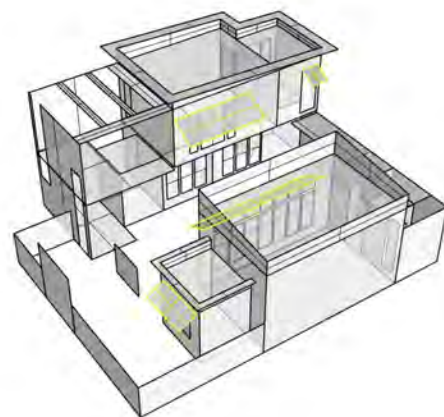
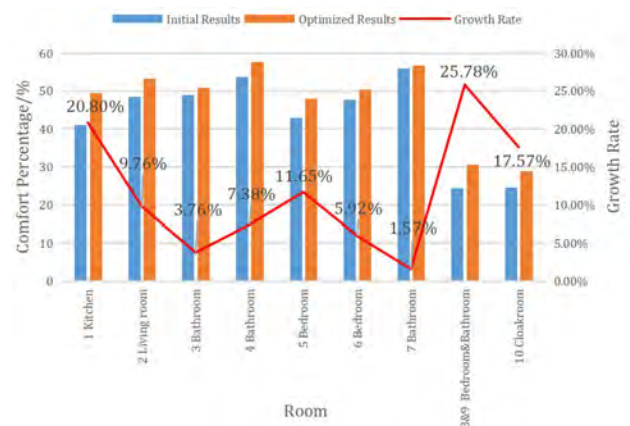*Figure 11. Inside of Courtyard*   *Figure 12. Sunshade*

Figure 13. Optimized model

Figure 14. Compared simulation results

DISCUSSION

Contributions

This research focus on indoor thermal comfort used numerical simulation and field survey methods to do a case study for healthy building. The simulation-

based on Ladybug and Honeybee plugins simulated indoor adaptive comfort for the whole year. Considering local environment effects, the field survey did on a summer day according to Chinese standards of T/ASC02 and GB/T 50785. The results of two different methods show the same trend that is hot indoors. This simulation is effective that also verifies other researchers' conclusion to a certain extent "Elwy et al. (2018)".

Comparing the results of numerical simulation with that of field survey, the indoor thermal environment of Yuedao Courtyard was hot, no matter in the whole year simulation or the typical day measurement. Thus, the natural ventilation of this standard building, Yuedao Courtyard, failed to provide a healthy indoor thermal environment.

Such a problem should be solved. Based on the field survey founding and passive building design thinking, the sunshades for the building is used to try to solve the hot indoors problem, by the way, reflect Lingnan architectural culture "B. Li, W. Guo, M.A. Schnabel, Z. Zhang & B. Li, W. Guo, M.A. Schnabel, T. Moleta (2020)".

The sunshades added on the windows help reduce indoors hot in summer. And due to the solar elevation angle is small during the winter, so it is almost no effect indoors lighting and heating by the sunshine in winter. Moreover, Jiangmen city located in south China in a "hot summer and warm winter" climate zone, so the vital issue should solve the hot indoors first "GB 50176. (2016)".

After comparing the initial and optimized results, the hot indoors problem could be solved in varying degrees. Even though the sunshades did not completely solve all the problems, but it is better than before. So it can be used in all the entrance facing the west Yuedao Courtyard. It has a particular contribution meaning.

Moreover, maybe it is too hot in south China, so only the shading method maybe not enough to form a comfortable indoor thermal environment to achieve a healthy building. However, more strategies could be found in Figure 12, except for the sunshades, the water pool and greening are also solutions for reducing indoor temperature. Because this optimization is based on the built Yuedao Courtyard under architecture design context, so minimal intervention is considered. More other strategies and situations could be done by the numerical simulation method. This explains that the simulation method could be used almost anywhere and anytime to some extent. Even if the field survey results are more authentic than simulation. The simulation can also evaluate projects under design in advance.

Limitations

The limitations of this paper, due to the field survey conditions, is the inability to collect data anywhere and anytime. Thermal environment measurement was not conducted in all the ten rooms, even though nine rooms are enough according to GB/T 50785.

CONCLUSIONS

This paper explores indoor thermal comfort for healthy building. Based on the literature review on healthy building and indoor thermal comfort, creating a healthy indoor thermal environment has been a pivotal point in this research. According to the objectives of Yuedao Courtyard and relevant requirements by standards, numerical simulation and field survey methods were used for evaluating the indoor thermal environment of Yuedao Courtyard. Their initial results were obtained. Furthermore, the optimization results were also obtained based on adding sunshades. After comparison and analysis, the main conclusions are as follows:

(1) The numerical simulation method could be used for evaluating indoor thermal comfort based on Ladybug and Honeybee plugins. The results have the same trend as the field survey.

(2) Yuedao Courtyard did not meet healthy indoor thermal environment requirements under natural ventilation. It is hot indoors, whatever during the whole year simulation or on the measurement day.

(3) The optimization measures could be considered by adding sunshades on the windows under the passive building context. It can be universally used for the standard building which entrance faced west.

(4) Numerical simulation is almost not restricted by working conditions, especially for buildings under design, which can evaluate whether the indoor thermal comfort condition is healthy or not. It is useful for designers to solve practical problems for better design.

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