The effectiveness of climate adaptation strategies in Chinese traditional courtyard house: a case study of the Yan's courtyard complex in Ningbo

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Abstract

Sustainable development is a theory and strategy for the harmonious development of the environment, economy, society, and culture. The study of the Chinese traditional courtyard house, one of the most prevalent types of traditional Chinese buildings, provides the cultural and climate-adapted sustainable development solutions needed for modern architecture. Traditional courtyard houses are formed, evolved, and shaped by the local climate as well as social and cultural influences. They are a valuable historical and cultural treasure and witnessed the long-term adaptation of working people to nature and the evolution of social life. In order to explore a sustainable development approach to modern architecture, a traditional courtyard house that is adapted to the local culture and environment is used as the subject of this dissertation's investigation. Both the history and culture and climate adaptation strategies are crucial for the sustainability of modern dwellings, both of which are discussed in this dissertation.

The focus of this dissertation is on Yan's courtyard complex in Ningbo, Zhejiang Province, China. A qualitative analysis based on literature research and field studies is used to analyse the history and culture and climate adaptation strategies of traditional courtyard houses. The temperature and humidity of Yan's courtyard complex during the hot and cold seasons are monitored in the field and Ecotect software simulations are employed for assessing the thermal, lighting, and wind environments of Yan's courtyard complex for the purpose of quantifying the effectiveness of climate adaptation strategies. The dissertation discusses the history, culture and climate adaptation strategies of traditional courtyard houses, with the aim of summarising the sustainable development patterns of courtyard houses. The findings reveal that in order to improve the living environment, ancient craftsmen took advantage of local natural conditions to build courtyard houses that were tailored to the local climate. The Chinese culture has long sought to unite man and nature, and as a result, ancient Chinese architecture was created with the goal of fostering this relationship and achieving a harmonious coexistence between the two. In the process of adapting to local natural conditions and passing on their culture, people have developed living space solutions that allow local culture and climate adaptation strategies to reinforce each other. The idea of unity with man and nature is embedded in traditional courtyard houses, and climate adaptation strategies enhance the living environment. Extracting useful experiences and solutions from traditional courtyard houses has positive implications for the conservation of traditional courtyard houses as well as the sustainable development of architecture.

Keywords: climate adaptation strategies; traditional courtyard house; physical environment of the building; simulation

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List of Figures

List of Tables

Content

1. Introduction and background

1.1. Research Introduction

On a global scale, sustainable development has become a strategic consensus for human society. Sustainable development is a theory and strategy for the harmonious growth of the environment, economy, society, and culture.

Energy consumption and sustainable development are related, and as the building industry contributes significantly to energy consumption, finding ways to cut emissions and save energy is a key focus in the industry today. Based on the report "China Building Energy Consumption Research Report" (China Building Energy Efficiency Association, 2021), the energy consumption or carbon emissions during the whole life cycle of a building is equivalent to the sum of the energy consumption or carbon emissions during the three phases of building materials production, building construction, and building operation. The main topic of this dissertation is building operation energy consumption, which generally refers to the energy used when a building is being used or operated. This primarily focuses on energy consumption in heating, air conditioning, ventilation, hot water supply, lighting, cooking, household appliances, lifts, and so on. In 2019, the total energy consumption of the whole building procedure in China was 2.233 billion tons of standard coal equivalent (tce), holding for 45.8% of the total national energy consumption, of which 1.03 billion tce was used in the building operation phase, holding for 46.2% of the total energy consumption of the whole building process (China Building Energy Efficiency Association, 2021). While it has slowed down from 2010 to 2019, the average annual growth rate of building operation energy consumption has continued to rise. This demonstrates that the existing building operation energy consumption is high, and still, there is a huge potential for energy efficiency in buildings. An essential and foreseeable question is how to decrease the amount of energy used when operating buildings.

The primary reason for the current high building operation energy consumption is the usage of a large number of technological means and mechanical equipment to accomplish building comfort. In the past few decades, as people's material living standards have enhanced, their demand for buildings is slowly moving from survival to health and comfort, and the objective of today's architectural design is to fulfil the comfort and health requirements of users (Borowski *et al.*, 2022). The environment inside a building has a significant impact on its comfort. The term "comfort of a building" in this dissertation primarily refers to the comfort of the building's thermal, wind, and lighting environments. It also means that the building must provide people with a healthy, safe, and comfortable indoor environment, including good thermal comfort, lighting, and ventilation. Given that building occupants are comfortable and healthy in an indoor environment is important (Fransson *et al.*, 2007), as people spend around 90% of their time in buildings (Shaikh *et al.*, 2013). A poor indoor environment can have an adverse effect on a person’s health as well as their mood, and productivity at work and in school. Technological developments have enhanced building technology, enabling people to create a more comfortable living and working environment through updated technical means. On the other hand, this increase in building technology has also brought the issue of over-reliance on technological means. Technology and mechanical equipment are frequently employed to improve living comfort when structures are used in hostile outdoor situations. Xu et al. (2020) focus on the widespread availability of heating, ventilation, and air conditioning (HVAC) systems brought on by improved building comfort as the major reason for the rapid rise in building operation energy consumption. While maintaining a comfortable indoor environment, these devices raise the energy consumption of building operations, contributing to a growing environmental issue and may even impact people's health, which does not fulfil the wishes and requirements of our society today for sustainable buildings. As people's material possessions keep on improving, their requirements for living conditions are slowly going up, but, in general, better building comfort plays an important role in building energy consumption. Therefore, the question of how to keep balance the occupants' requirements for building comfort with building energy efficiency becomes a significant issue, and a way to solve the contradiction between building comfort and sustainability is required.

One of the key reasons for the contradiction between attaining building comfort and lowering building operation energy consumption is the neglect of adaptation to the local environment. A climate adaptation strategy permits the usage of free renewable natural energy resources, maintains the comfort of the building interior in an appropriate range, decreases the requirement for mechanical equipment, and ultimately results in a reduction in the building operation energy consumption (Gou *et al.*, 2015). Climate adaptation strategies are frequently used in traditional architectural design throughout the world due to their perfect adaptation to climate and environment (Juan *et al.*, 2019). Traditional Chinese architecture was made and designed based on the social and climatic conditions at that time and includes a significant deal of experience and wisdom, with the benefit of being adjusted to the local environment and climate. Most modern structures rely on energy-intensive technical equipment to provide a comfortable inside environment while providing resistance to hostile external temperatures (Yang *et al.*, 2022). Compared to modern architecture, traditional architecture has been practiced and developed to get harmony with the local environment and climate. Traditional Chinese architecture has always required harmony between man and nature. Looking back at the history of architecture, from the cave dwellings of the primitive period to the later development of a variety of buildings with regional characteristics, all symbolize the traditional Chinese concept of the unity of man with nature in the environment, and all respect and adapt to the local environment. To improve the living environment and promote harmony between architecture and the environment, traditional architecture is relied on the natural conditions of the area with minimal energy consumption (Liu *et al.*, 2019). Traditional architecture has developed over hundreds of years in response to the local environment, climate, topography, and culture. It has also become the most suitable sort of building for the local climate and living requirements, leading to a wide range of representative traditional regional and cultural buildings, which will offer a comfortable environment with minimal energy consumption. Several studies (Hatamipour and Abedi, 2008; Du *et al.*, 2014; Gou *et al.*, 2015; Chiou and Elizalde, 2019) have reflected that traditional and historical buildings have considered and built many climate adaptation techniques to adjust into the local climate, and such strategies can be considered by modern architectural designs to get sustainable concepts. It is evident from this that the solution to the conflict between energy consumption and comfort in modern buildings is to decrease the reliance on mechanical equipment and learn from the flexible usage of natural resources, such as solar radiation, natural ventilation, and natural light, in traditional buildings. A precious resource for the sustainable development of modern buildings is traditional architecture, with its practical and adaptable tactics and approaches to the local climate and environment, adhering to the principle of harmony with nature (Xu *et al.*, 2016).

The concept of development is rich in values, cultures, contexts, and time features (Soini and Dessein, 2016). Development and culture are inextricably linked, and culture is a critical cornerstone for ensuring sustainable development. The notion of sustainable development is increasingly tending to be separated into various dimensions: environment, economy, society, and culture. This acknowledges the importance of culture to sustainable development. It is evident from this that the significance of culture to sustainable development should also be focused on. Traditional buildings safeguard the historical and cultural heritage of society and are a significant medium to promote cultural sustainability (Wu *et al.*, 2016). The architecture of different regions is affected by the local ethnicity, environment, and culture, and holds a clear cultural specificity (Shan, 2022). An invaluable tool for investigating the climate adaptation and cultural sustainability of buildings is the study of traditional dwellings (Yan *et al.*, 2022). Traditional dwellings are one of the widely distributed, diverse, and adaptable kinds of traditional buildings. İpekoğlu stated that the major critical witness to past lifestyles is the city's historical sites and traditional residences (İpekoğlu, 2006). As one of the most important forms of Chinese dwelling, traditional courtyard house is a significant aspect of Chinese historical and cultural heritage and an important carrier of historical culture. Traditional Chinese architecture has changed, evolved, and been incorporated over thousands of years to reflect the features of the eras, nations, and areas. Traditional courtyard house holds significant historical information, whether it is the layout of a building complex, the form of the building layout, or the techniques considered in the traditional dwellings' construction, all of which have a specific historical and cultural value. Traditional courtyard house has observed significant changes and development of history in several regions, and represented the history and culture of the ancient Chinese nation and its infinite artistic charm, making it an invaluable and precious historical and cultural resource for China. The preservation of traditional courtyard house and the inheritance of their construction experience includes the preservation of history and culture and can offer solutions to contemporary sustainable development issues (Qtaishat et al., 2020).

Ningbo, Zhejiang Province, with its hot summers and cold and humid winters, lacks research on exploring the traditional dwellings of the region, and the local traditional dwellings are majorly traditional courtyard houses, therefore this dissertation takes traditional courtyard houses in Ningbo as a study object. This dissertation considers a qualitative analysis on the basis of literature and field research to assess the sociocultural and climate adaptation techniques for traditional Chinese traditional courtyard houses in Yan's courtyard complex in Ningbo; the temperature and humidity of Yan's courtyard complex during the hot and cold seasons are monitored in the field and Ecotect software simulations are used for assessing the thermal, lighting, and wind environments of Yan's courtyard complex, in order to quantify the effectiveness of climate adaptation techniques.

In addition to highlighting architectural designs and building experiences that are adapted to the local culture and climate, revisiting traditional homes can help people rethink the relationship between social, cultural, and climatic environments and buildings. It can also highlight the shortcomings of traditional courtyard houses with regard to comfort, offer directions for enhancing the existing problems of high energy consumption and contribute to the inheritance of social culture. As a whole, it is a guide to the conservation and restoration of traditional buildings, while also promoting the sustainable growth of modern buildings.

1.2. Research questions and aim

This dissertation places a great emphasis on traditional courtyard houses in order to discover sustainable ways of traditional buildings. Traditional courtyard houses are an important historical and cultural heritage that serves as both memories of traditional lifestyles and cultural symbols. Being a key component of cultural heritage, the preservation of the tangible and intangible values contained in traditional buildings and the construction of local identities is a significant part of achieving sustainable development goals. Traditional courtyard houses are vital historical and cultural heritage, and paying attention to these typical traditional buildings is beneficial to understand and inherit Chinese traditional culture. Studying the impact of climate adaptation strategies adopted in traditional courtyard houses on the comfort of buildings is useful in increasing the comfort of traditional courtyard houses and is important in promoting the sustainable development of buildings.

This dissertation analyses this question by exploring the relationship between social culture and traditional courtyard houses in Ningbo, looking for and identifying climate adaptation strategies in traditional courtyard houses and assessing the effectiveness of climate adaptation strategies, ultimately drawing out sustainable solutions suitable for the cultural and climate adaptation of traditional courtyard buildings. Due to the lack of research on traditional courtyard houses in Ningbo, Zhejiang Province, China, this dissertation utilised traditional courtyard houses in Ningbo as a case to explore how traditional courtyard houses were adapted to the local climate, environment, and culture. Local courtyard houses in Ningbo were affected by the local climate, culture, and historical constraints, with wooden structures, often employed as the primary structural load-bearing structure, with a courtyard layout and high walls and narrow alleys. Moreover, Yan's courtyard complex shares these architectural characteristics. This dissertation primarily aims to summarise local climate adaptation strategies through the analysis of a case study, Yan's courtyard complex, and in the process to examine the strengths and weaknesses of the comfort of historic buildings. This dissertation attempted to comprehensively evaluate the influence of the climate adaptation strategies of Yan's courtyard complex on the environmental comfort of the traditional building regarding thermal, light, and wind environments, to present the shortcomings of the building's comfort, and to synthesise effective climate adaptation strategies. Current research has not studied the culture of traditional courtyard houses enough and lacks in-depth analysis and interpretation, so this dissertation concentrated not merely on the climate adaptation strategies utilised in traditional courtyard houses, but also on the links between these strategies and local culture. A focus on adaptation strategies used in traditional courtyard houses can aid in providing culturally and environmentally sustainable solutions for modern architecture.

This dissertation raises the following questions:

1. What climate adaptation strategies were used to adapt to the local climate and environment in Yan's courtyard complex?

2. How do climate adaptation strategies relate to the philosophical idea of the unity of man with nature?

3. By combining climate adaptation strategies with the idea of the unity of man with nature, what sustainable methods of adapting to local culture and climate can be summarised?

1.3. Thesis structure

This dissertation consists of seven chapters, organised as follows: chapter 2 reviews the relevant literature on climate adaptation strategies for traditional buildings, chapter 3 describes the research methodology and specific research methods used in this dissertation; chapter 4 details the research cases , Yan's courtyard complex, in this dissertation, climate adaptation objectives in Ningbo, and the ancient philosophical concept ; Chapter 5 describes the results of field monitoring and thermal, wind and lighting environment simulations; Chapter 6 provides further analysis of the results; Chapter 7 summarises several main conclusions.

2. Literature review

2.1. Introduction

This chapter reviews, organises, and categorises the research on the adaptation strategies for traditional buildings and the physical environment of traditional buildings, with an aim to determine the current state of research on adaptation techniques for traditional buildings and summarize the current problems with such type of research. For this purpose, this dissertation focuses on research on climate adaptation strategies for traditional buildings in several regions, summarises the research objectives of such dissertations, and assesses the relevant physical environment of traditional buildings.

The study was conducted by searching several journal and book databases (Taylor & Francis, Science Direct, Sustainability, AIChE, SpringerLink, MDPI, Chinese National Knowledge Infrastructure) and by consulting the books of the University of Nottingham Ningbo Library and the Shanyuan Library. The literature search included the keywords "building", "thermal comfort", "light", "wind", "sustainable", "courtyard", "traditional ", "Ningbo", "historical", "the unity of man with nature ", "culture" and combinations of these keywords. This research focuses on a literature that focuses on the building physical environment of traditional buildings.

In the past few years, reducing energy consumption in buildings has become a hot topic of concern for all sections of society. The majority of modern buildings are built and designed without considering the influence of the local environment and climate, which results in a high level of energy consumption for building operations. Traditional buildings, instead, are unique in not relying on energy consumption and use Climate adaptation strategies to deal with the harsh natural environment of the local area. Traditional buildings were constructed in a technologically undeveloped environment, where people could not use technology to get comfort in the indoor environment, therefore, the influence of the local environment on indoor comfort had to be considered by builders or achieved by the conventions. The local environment and culture were carefully measured in designing and constructing traditional buildings, which have been tested over time through practice and adapted to the local climate and culture. Due to a lack of mechanical equipment, traditional vernacular buildings in Nepal have been identified in four distinct climate zones. To achieve thermal comfort conditions, these traditional buildings use a variety of solar passive methods (Bodach et al., 2014). Nine old houses situated in three regions of Israel have been reflected to possess climate adaptation techniques, as they regulate the impact of external temperatures on indoor temperatures, offering the required thermal comfort indoors, and such climate adaptation techniques offer meaningful value to residential buildings of energy efficiency and relief of negative impacts on the environment (Hamza and Paz, 2016). The traditional dwellings in the Qinba mountains of China have adjusted as per the local climatic characteristics by using technical measures, like small size doors and windows, garret space, and large galleries to successfully get harmony between the dwelling and the climatic environment, which is one of the major factors for sustainable development (Juan et al., 2019). The climate of the Dong region of China is well adapted by the local traditional residences in their forms, materials, and structures, like small windows and doors, overhead roofs and large eaves, showcasing the concept of a man living in harmony with nature (Zhang *et al.*, 2022). The orientation of structures, courtyards, and shade are only a few examples of the many climate adaption tactics that traditional architecture represents. These strategies enhance living comfort and have a sustainable nature.

A substantial amount of literature is available on the climate adaptation of traditional buildings. These studies recommend the significance of traditional climate adaptation strategies to improve the comfort of buildings and reduce building operation energy consumption. Considering fourteen old buildings in cold Iran as a study case, Tamaskani Esfehankalateh et al. (2021) assessed the local climate and certain interior characteristics of the houses to find out the beneficial Climate adaptation strategies to offer indoor thermal comfort. The research findings reflect that historic houses conform to contemporary models of bioclimatic strategies and fulfil the comfort requirements of today's occupants Hatamipour and Abedi (2008) evaluated natural cooling methods for ancient buildings adapted to the hot and humid climate of southern Iran, by considering which people can live comfortably in the hot season without any air conditioning equipment. Borong et al. (2004) checked temperatures and wind speeds of four typical traditional residences in the Wannan region in summer, determined some incorrect opinions regarding the traditional Chinese dwellings, and suggested some design principles for traditional vernacular residences in Wannan region, where shading and insulation are important to enhance thermal comfort in summer, while natural ventilation only acts as a secondary method. Traditional dwellings in the Wu-style buildings of Jinhua, China, were considered as a sample study by Yan et al.(2022), who highlighted that Wu-style buildings use climate-adaptive methods for heat dissipation, insulation, ventilation, and lighting, containing the flexible use of slender grey space forms and large eaves for internal and external space transitions, effectively enhances the building's wind, thermal, and lighting environments. Such researches reflected that the strengths of traditional buildings were that they were better adapted to the local environment and climate, and a direct link between the climate adaptation of traditional buildings and the comfort of buildings.

2.2. Current research on different regions

Studies on climate adaptation strategies for traditional buildings have been conducted in many nations, including China, France, Greece, India, Iran, Spain, Vietnam, and many other countries (Nguyen *et al.*, 2011; Oikonomou and Bougiatioti, 2011; Du *et al.*, 2014; Rubio-

Bellido *et al.*, 2015; Xu *et al.*, 2016; Zamani *et al.*, 2019; Su, 2020), and such studies jointly reflected that traditional buildings were well adapted by their local environment and climate, confirming the effectiveness of Climate adaptation strategies.

Some studies (Hao *et al.*, 2019; Zamani *et al.*, 2019) have assessed traditional courtyard houses to evaluate the variation in temperature and humidity inside and outside the courtyard and have demonstrated that courtyard buildings have better thermal adaptation in summer. Zamani, et al. (2019) investigated the inner and outdoor thermal conditions of a typical traditional Iranian courtyard house in order to examine the thermal performance of courtyard buildings. The study simulated indoor thermal performance in several thermal zones and compared microclimates inside and outside the courtyard. The results displayed that traditional courtyards could offer a cool microclimate in summer and concluded some climate adaptation strategies were suitable for local buildings.

Historic dwellings were the major focus of this study, and these studies (Nguyen *et al.*, 2011; Oikonomou and Bougiatioti, 2011; Rubio-Bellido *et al.*, 2015) examined traditional dwellings in multiple climates. Nguyen et al. (2011) performed an in-depth survey of six traditional historic buildings situated in three regions of Vietnam with hot and humid climates and evaluated the physical environment of the buildings by field measurements and simulations. The research findings reflected that Vietnamese vernacular houses have innovatively adapted to the local environment by using various climate-responsive strategies, containing natural ventilation, building orientation and shape, and solar shading, and the effectiveness of climate-adaptive strategies was confirmed. In order to comprehend climate response strategies for historic housing in Cádiz, Spain, in a mild Mediterranean climate, Rubio-Bellido et al.(2015) qualitatively and quantitatively determined bioclimatic design strategies applied to these historic buildings. The findings showed that historic housing in Cadiz was successfully adapted to the local natural circumstances through a variety of climate-responsive measures, but that the coping mechanisms for global warming need to be enhanced. Oikonomou and Bougiatioti (2011) performed research on the forty traditional buildings of the 19th and early 20th centuries in the town of Florina, north-western Greece with a cold and wet winter and a warm and dry summer. The type, form, materials, and construction techniques of these buildings were assessed along with the thermal and visual comfort conditions of these buildings. The study summarised the design principles linked with bioclimatic buildings, and these are available to renovate old buildings or design new buildings in traditional settings. Traditional dwellings have been researched in a variety of climates, but fewer studies have evaluated traditional dwellings in regions with hot summers and cold winters.

The indoor thermal comfort and climate adaption techniques of traditional structures in different parts of China have been analysed and explored (Du *et al.*, 2014; Zhu, 2018; Zhang *et al.*, 2022) during the last few decades by field surveys and measurements, and along with these researches have reflected that traditional Chinese buildings have considered effective strategies to adapt to the local environment and climate.

Various studies (Zhu, 2018; Hao *et al.*, 2019) have discussed this topic from the perspective of villages. Zhu (2018) used the Shaoxing Zhongxie village as a typical example to investigate the efficacy of spatial-climatic adaptation from the viewpoint of a settlement group. The study analysed the passive environmental creation strategies of traditional villages in Shaoxing at both settlement and architectural levels, and on the basis of qualitative analysis, confirmed some of such strategies using the village of Zhongxie as a practical case study.

Major researches (Du *et al.*, 2014; Zhang, 2015; Xu *et al.*, 2016; Su, 2020; Xu *et al.*, 2020; Zhang *et al.*, 2022) on single buildings are focused on traditional Chinese dwellings. Du et al. (2014) performed field investigations to study microclimates in vernacular houses by using a 120-year history of Yang's house in Shuangjiang Town, Chongqing China as a case study. The research reflects that creating comfortable conditions for the occupants is doable; simulation can predict the microclimate of the building. Su (2020) performed field research on nine key traditional dwellings in the Qinling Mountains. In order to enhance the unreasonable design, two dwellings, one old and one new were chosen for physical environment testing in winter and summer for quantifying the objective problems. In order to get the suitable ecological factors, the ecological factors of the dwellings were modelled in three aspects: the courtyard space, the individual buildings, and the detailed practices. A strategy for the inheritance of the ecological factors of traditional dwellings in the Qinling Mountains was deduced at last. Zhang et al. (2022) determined climate-responsive strategies considered in traditional Dong dwellings in Northeast China and examined the influence of such strategies on the interior environment and energy consumption. The findings showed that traditional Dong dwellings could effectively regulate indoor temperature fluctuations. The traditional Dong dwellings can well adapt to the local climate with regards to form, material, and structure; moreover, the study suggested a residential adaptation strategy that effectively adapted to the local Dong climate.

Few studies (Xu *et al.*, 2016; Li and Liu, 2021) have discussed public buildings in ancient China. Xu et al. (2016) chose six typical ancient wooden buildings in northern China and computed their thermal environment during typical summer and winter seasons to get more environmental concepts and climate adaption strategies. The results showed that ancient halls were more focused on reducing negative climate impacts than on utilising positive climate resources. The findings identified their climate-responsive design choices.

Few researches have examined adaptation strategies for traditional Chinese buildings in the Zhejiang region (Zhang, 2015; Zheng and Chen, 2020). Zhang summarised the shading forms of typical traditional dwellings in Zhejiang and assessed the comprehensive effect of shading by software simulations, giving suggestions and measures for the renovation and design of shading of dwellings in Zhejiang. To research the methods used by traditional residential architecture in the Zhoushan Islands region of Zhejiang Province to adapt to climatic change, Zheng and Chen (2020) used the fishing community of Qingbang Island in Shandong Province. The study used "climate-architecture" theoretical analysis, dwelling layout, and morphological analysis to assess the adaptation strategies of the local architecture to the surrounding environment. The study has summarised six patterns of architectural design for traditional dwellings on Zhoushan Island.

These studies recommended that effective climate adaptation strategies were available for traditional buildings and that climate adaptation strategies could support maintaining better comfort in buildings without mechanical ventilation for energy-saving purposes. Investigating climate adaptation techniques used in traditional buildings can offer recommendations for the construction of modern buildings in the respective regions, contributing to local energy efficiency and sustainable development. Climate adaptation strategies are regional in nature, and a variety of climates and environments will adopt diverse climate adaptation strategies, therefore the research on climate adaptation strategies for traditional buildings should be regionally specific. Zhejiang Province in China is situated on the Chinese coast and within a hot summer and cold winter, climate zone and the problem of building comfort should be of particular concern in this climate. A large number of traditional buildings are present in this region, but only limited research has been performed on climate adaptation strategies for traditional buildings in this region.

2.3. Current research on traditional buildings

In the research of climate adaptation and comfort of traditional buildings, there are three major directions: (1) Renewing and Retrofitting Traditional Buildings with regards to Energy Consumption and Indoor Comfort; (2) Experience of climatic adaptive design of traditional architecture and traditional climate concepts inherent; and (3) The effectiveness of climate adaptation strategies.

(1) Renewing and Retrofitting Traditional Buildings with regard to Energy Consumption and Indoor Comfort

This type of research evaluates the current level of comfort in traditional buildings by field research and monitoring, analyses the existing deficiencies in energy consumption and comfort in traditional buildings, and investigates what energy-saving measures can be considered to enhance and secure the traditional building environment while minimising changes their appearance and structure.

Orehounig and Mahdavi (2011) gathered data on the energy usage and thermal environment of five historical hammams over roughly one year, determined problems with the energy consumption and thermal environment of such buildings, and considered simulation software to determine the thermal performance and energy consumption outcomes of three of these hammams. The simulations' findings demonstrate the potential for improvement considers to reduce the energy consumption and thermal environment of these buildings. Burattini et al. (2015) performed research on the influence of four passive strategies for retrofitting historic buildings on the energy consumption of an ancient public library situated in a town near Rome without any modification on the building structure to learn how to obtain sustained energy savings on historic Italian buildings by simple remodelling interventions. The findings reflect that four passive strategies create a favourable influence on the building operation energy consumption. Onecha and Dotor (2021) considered a dynamic simulation technique to assess the influence of four natural and mechanical ventilation methods on the improvement of comfort in a church in Barcelona, in order to explore measures for enhancing the summer comfort of the ancient building. Wang (2021) simulated and assessed the wind, light, and thermal environments of traditional dwellings in the mountainous areas of Jinan with regard to street layout, space combination, courtyard scale, building floors, and envelope structure, in order to determine the problems and disadvantages of the existing spatial comfort of the houses and suggest adjustment targets. After adjustment, the indoor wind, light, and heat environments have been enhanced.

This research assesses the existing energy consumption and comfort problems of traditional buildings by evaluating the current situation of traditional buildings in a specific region and suggests energy-saving retrofitting strategies to enhance the comfort of traditional buildings in response to these issues. These studies summarise the existing conservation strategies for energy efficiency and renewal of traditional buildings, which are significant guidelines for the current conservation of ancient buildings, but these researches mainly focus on the current state of conservation of traditional buildings and less on the climate adaptation strategies inherent in traditional buildings.

(2) Experience in climatic adaptive design of traditional architecture and traditional environmental concepts inherent

This research evaluates traditional architecture from the viewpoint of architectural forms, building materials, and ecological concepts through qualitative research, like field investigation, with an aim to discover the experience of climate adaptation design and traditional environmental concepts inherent in traditional architecture.

Qualitative research on traditional climate adaptation contains research on traditional environmental concepts and climate adaptation strategies.

Since the early 2000s, culture has also been acknowledged as the fourth pillar of sustainable development (2022). According to Feng and Xiao (2021), the values and beliefs of architecture culture are the major decisive elements to preserve vernacular architecture in its original form. Any development is unsustainable without the combination of culture into sustainable development policies (Postalcı and Atay, 2019). Traditional buildings are a significant historical and cultural heritage and their research are significant for the sustainability of the culture. Moreover, by studying ancient philosophical concepts, a critical aspect of culture, more support can be given for the sustainable development of modern architecture. Almodovar-Melendo and Cabeza-Lainez (2018) et al. determine the relationship between the formalisation of historical Chinese buildings and nature, reflecting that there is an empirical wisdom in historic Chinese buildings that is reflected in the fact that humans must always live in harmony within the natural environment. To confirm this concept, Beijing's traditional urban layout was subjected to environmental analysis, the outcomes of which proved that energy-efficient and sustainable urban solutions with favourable environmental values can be created by a harmonious link between climate and culture. Zhao and Liu (2010) explain the simple green concepts of ancient Chinese architecture, containing the idea of capital planning in imitation of the celestial stars, the idea of architectural frugality, adapting to local conditions, the aesthetic appeal of nature, and the environmental awareness in feng shui, and highlight the historical limitations of the green concepts of ancient Chinese buildings. Chen and Wu (2009) determined the "unity of man with nature" concept, the "peach blossom spring" ideal, the "world-in-a-pot" model, and Feng-shui theory principles and models of Chinese landscape architecture and found out their implications for the sustainable landscape architecture growth. They recommend that such principles and models can offer beneficial guidelines for the sustainable development of landscape architecture.

Another part of the research mainly gives focuses on the climate adaptation strategies of traditional buildings, with an aim to summarise traditional climate adaptation strategies and offer useful sustainable strategies for modern urban housing design.

Field research and literature collection were the major research techniques considered in these researches, evaluating the architectural features like site selection, plan layout, and detailed construction. He et al. (2020) evaluated the adaptation of buildings to the rainy climate and frequent flooding in the Baiyangdian area, taking the local traditional dwellings as an instance, and determined the ecological wisdom of traditional dwellings and enriched the research dimension of architectural climate adaptation studies by exploring the site and scale characteristics, plan layout, façade types, and building structures. The research shows that traditional residential buildings in the Baiyangdian area have clear characteristics of rain and flood adaptation. Wang and Zhu (2021) considered the field investigation techniques and literature review to summarise the characteristics of the architectural layout patterns, envelope material forms, and construction techniques of the traditional dwellings in northern Yangtze-Huaihe Region, Anhui Province and assessed the climatic adaptation strategies embodied in such dwellings through the simulation of Ecotect software. This research summarises the climate-adaptive ideas of local people by considering natural climatic resources and offering new ideas for the design and construction of modern buildings for sustainable development. Photographs and interviews with former residents are also valuable research methods. Victoria et al.(2017) conducted an observation, and photographic analysis and interviewed former residents of 16 traditional longhouses in Malaysia, with a hot and humid climate. This research reflected that the design of traditional longhouses with regards to lighting, ventilation, and materials is beneficial in adapting to the local climate and that these climate adaptation strategies can be used to design modern homes, which are considered a good case of past bioclimatic building design.

Based on these researches, traditional buildings do have some advantages in energy efficiency and thermal comfort, and the design of traditional buildings is normally more responsive to the local environment and builds a more comfortable environment for users. Thus, traditional buildings contain climate adaptation strategies and ecological concepts of harmony with nature, which have value for the energy-efficient design of modern buildings. On the other hand, these studies only summarise a few strategies and do not evaluate the effectiveness of these strategies and their influence on comfort. A qualitative summary of climate adaptation strategies is not sufficient to comprehend the influence of these strategies on the comfort of buildings, as a specific climate adaptation option may have different impacts on the wind, lighting, and thermal environment of a building. Therefore, it is only by assessing the effectiveness of these strategies that feasible and effective adaptation solutions can be determined and ultimately applied to the sustainable development of modern buildings.

(3) The effectiveness of climate adaptation strategies

These studies rely on a summary of adaptation strategies for traditional buildings and an evaluation of the effects of these strategies on the indoor environment by using quantitative studies including field monitoring and computer simulations, to find out the energy-saving potential of traditional buildings.

In order to provide useful environmental adaptation strategies for modern architectural design, Kubota et al. (2017) monitored the temperature and humidity in the internal courtyard and adjacent living hall of a Chinese shop situated in Malaysia and assessed changes in thermal environments of houses and thermal comfort in living halls. They come to the conclusion that various courtyard configurations serve distinct purposes in enhancing internal thermal comfort and advise enclosed, cross-ventilated courtyards for contemporary residences in hot and humid areas.

Gou et al. (2015) summarised the climate responsiveness technique for a traditional house in Xinye, China, and kept a check on indoor air temperature, relative humidity, wall temperature, and wind velocity and simulated ventilation conditions and thermal environments through EnergyPlus software. The results reflect that the climate adaption strategy is effectively responsive to the building climate, mainly in hot weather conditions, based primarily on natural ventilation, shading, and insulation of the building envelope. Through field research and temperature and humidity monitoring, Chiou and Elizalde (2019) compared the indoor thermal environments and climate adaptation strategies of three different styles of rural historic houses in Taiwan in order to understand sustainable design strategies suitable for the hot and humid local climate. The study reflects that there is a huge potential for building low-energy places by using these environmentally adaptive design strategies.

Such a type of study suggests a number of building design strategies to adapt to local climates, and assesses the effectiveness of such strategies through field research, field monitoring, or software simulations by using a particular study case as an example.

In summary, such studies mainly focused on energy-efficient retrofitting of traditional buildings or on qualitative analysis of traditional environmental concepts or climate adaptation strategies embodied in traditional buildings, with only a few studies qualitatively explaining climate adaptation strategies for traditional buildings.

2.4. Current research on the physical environment of traditional buildings

In order to comprehend the effectiveness of traditional climate adaptation strategies, the physical environment of traditional buildings requires to be assessed and evaluated. The physical environment of buildings is categorized into three major components: thermal, lighting, and wind environments. The thermal and wind environments are the significant contributors to developing comfort and thus, they are the most potentially and frequently discussed topics. The building's lighting environment is also discussed as another reason for building comfort.

(1) Thermal environment

Solar radiation is the major direct source of heat to the building and impacts the interior temperature. In the cold season, the sun offers thermal radiation for the building, which increases the indoor temperature and enhances thermal comfort; in the hot season, if no shading measures are taken to counteract the impact of solar radiation on the interior, solar radiation will cause high indoor temperature, leading to discomfort and even affect the health of the users. Buildings should therefore shield themselves from sunlight in the summer and gather solar energy in the winter. Solar radiation directly influences outdoor thermal comfort, and in courtyard buildings, the courtyard, as an outdoor space, is significantly influenced by solar radiation, therefore, shading is an important factor to decrease the air temperature in the courtyard (Zamani et al., 2018).

The building is a place where people live for a long time, which can have a huge influence on their health and work efficiency. Indoor environments that are too hot or too cold for long periods of time can directly decrease the productivity of the occupants and even cause various health issues. In an indoor environment with poor thermal comfort, people consider modern equipment to regulate indoor temperature and humidity to improve the interior thermal environment, which also leads to a rise in building energy consumption. Thermal comfort is a significant criterion to assess the thermal environment of a building. Two common thermal comfort models are often used to obtain the thermal comfort of buildings: heat balance and adaptive models. While adaptive models are generally based on data from field studies and are suited for evaluating buildings with natural ventilation, heat balance models are created using laboratory data and are more suitable for structures with mechanical temperature control.

Cantin, et al. (2010) examined the thermal environment of 11 historic houses over a period of one year on the basis of temperature and relative humidity measurements of the buildings. This field survey reflected that the design and architectural elements of such historic houses considered the local climate and environment with an aim to maintain thermal comfort in the absence of mechanical systems.

Mousli and Semprini (2015) studied the impact of the building structure and natural ventilation techniques on the thermal comfort of buildings in two kinds of traditional houses in Damascus in the hot and arid climate of the Mediterranean region. By measuring the air's temperature, humidity, and velocity, as well as its velocity and comfort levels, they were able to study the interior's thermal environment. The study reflected the significance of traditional structures and materials.

Toe and Kubota (2015) performed research on the thermal environment of the interiors of two traditional Malay timber houses and two traditional masonry Chinese shop houses by measuring temperature and relative humidity, in order to evaluate traditional passive cooling techniques in Malaysia. The study summarises potential passive cooling techniques for traditional Malaysian buildings, containing night ventilation, roof or ceiling insulation, window and wall shading, small courtyard concepts, and microclimate modifications.

(2) Lighting environment

The lighting environment includes the intensity of light and the distribution of spatial brightness. Although it does not directly impact people's safety and survival but affects people's comfort and their psychological feelings. Being in a dark environment for a long time can make people mentally depressed and influence their work and study efficiency, while bright natural light can allow people to feel more comfortable and enhance the comfort of the room. Utilizing natural light to its maximum potential can enhance indoor comfort and save energy usage since sunlight is the primary source of natural light in buildings and artificial lighting can increase a building's energy consumption.

Belakehal et al. (2004) qualitatively assessed the sunlight strategies, the kinds, and the lighting environment of urban streets and buildings in hot and arid regions of the Islamic world. The study noted the significance of sunlight in relation to heat, cooling, and ventilation and summarised various sunlight exposure strategies used in the traditional local built environment.

To evaluate the natural lighting environment of traditional courtyard buildings in Beijing, Yao, et al. (2021) created models of typical Beijing courtyards, simulated natural light in these models on multiple time-by-time bases all over the year, and performed a comparison on the impacts of window materials on the interior lighting environment. The study determined that paper windows have the benefits of decreasing seasonal differences in illumination, enhancing illumination uniformity, and decreasing the chance of glare in the east and west chambers in contrast to glass windows.

(3) Wind Environment

Ventilation can enhance the quality of indoor air, which affects users' comfort and health. Poorly ventilated indoor air can harbour bacteria that can create health issues. Indoor building materials and occupants emit indoor air pollutants, and good ventilation can dilute air pollutants. During epidemics, viruses are often taken into account while designing buildings, and lack of air circulation can also create viruses to spread in the air creating infectious diseases. Ventilation will also enhance indoor thermal discomfort, and people normally open windows to lower indoor temperatures during the hot seasons. Night ventilation can be considered to lower the cooling load of the building and enhance the thermal comfort of the occupants (Imessad et al., 2014).

Chiou and Elizalde (2019) emphasised the impacts of three climate-responsive design techniques on the thermal comfort of buildings and temperature and humidity fluctuation patterns and comfort percentages, the difference between exterior and interior temperatures, and the time lag between exterior and interior temperature were the major focus in the analysis.

In order to simulate the wind environment in a historic building in Palermo, Italy, Balocco and Grazzin (2009) considered CFD tools, including airflow patterns, distribution and velocities, and air temperature distribution within the building. The effectiveness of ancient natural ventilation systems in historic constructions was ensured and some suggestions for natural ventilation in modern buildings were also recommended by this research.

Wang, et al. (2021) considered Envi-met software to simulate and assess the wind environment of traditional villages; they also simulated and examined the indoor wind environment of typical courtyard buildings; and at last, they assessed and compared the wind environment of wells and lanes under a variety of scale combinations. The study's findings revealed a strong correlation between traditional courtyard homes in southern Hunan's form, size, ventilation efficiency, and climatic adaption.

The above researches have only explained single aspects of the thermal, wind, and lighting environments, with the thermal environment, in particular, always being explained more often. Fewer researches have explained two or three aspects of the thermal environment as a whole. Among these, thermal and wind environments are more frequently explained.

Kubota et al. (2017) focused on the thermal comfort of the courtyard of a traditional Chinese shophouse in Malaysia, with significant attention to the impact of the interior courtyard on temperature and humidity. Brief research was also performed for the wind environment, the outcomes of which reflected that different wind velocities indicated that the yard performed a variety of thermal functions, building different indoor thermal conditions. Hao et al. (2019) evaluated the impact of courtyards on the thermal and wind environments of a traditional vernacular house in Chongqing through field measurements and software simulations. The measurements demonstrated that the courtyard enhanced the building's comfort in summer, with peak summer temperatures being greatly decreased, but that the direct solar radiation received by surrounding rooms was also disallowed by the courtyard in winter. The simulation outcomes reflected that the natural ventilation of the courtyard can be enhanced through suitable openings in the ground. Di Tur et al. (2017) considered the contribution of ancient climatic strategies to enhance indoor thermal comfort and rational energy usage in summer by simulating the thermal and wind environment of an ancient Infants' Tower located in the Alhambra in Granada. The findings recommended that natural ventilation techniques in historic buildings could enhance the comfort and air quality of the building.

Fewer studies have explained wind and lighting environments. Li et al. (2022) considered Ecotect software to simulate the lighting environment of modern and traditional Bai dwellings in Gusheng Village, Yunnan Province, and to qualitatively assess the wind environment of such dwellings for evaluating the environmental adaptations of local dwellings. The research offered various important findings and provided a comprehensive understanding of spatially sustainable techniques for traditional housing by performing a comparison of the spatial configuration and adaptation to the natural environment of traditional vernacular and modern housing.

Few studies have evaluated the thermal, wind, and lighting environments of traditional buildings in an integrated method. Through field research, Yang (2018) extracted the architectural prototypes of Guanzhong traditional houses with regard to pedestal, structure, roof, and exterior space. Moreover, computer software was considered to simulate the thermal, wind, and lighting environments of the buildings, with an aim to summarise the energy-saving experience of traditional Guanzhong houses at three levels: planning and site selection, building units and construction techniques, and updating and enhancing the shortcomings.

Jin and Zhang (2021) evaluated the thermal and wind environments of Dong village traditional houses by determining temperature, humidity, wind velocity, wind direction, and PM2.5 and CO2 and assessed satisfaction with the thermal, lighting, sound, and wind environments of the buildings through questionnaires. The findings demonstrated that these traditional stilt houses have the ability to adapt to the local climate and that residents hold a greater ability to adapt to thermal comfort under natural ventilation than urban dwellers.

Ventilation, thermal comfort, and solar radiation should be explained together, as they will impact and relate to each other by influencing the thermal environment. However, all three affect the comfort of living, and satisfying a single factor does not ensure a better living environment; thus, it is significant to explain all three themes together to effectively and properly use the thermal environment of buildings.

Research on traditional buildings has emphasised the thermal environment, followed by the wind environment, which are the two important factors that affect the thermal environment with less discussion on the lighting environment. Several researches have explained only one of the thermal, lighting, and wind environments, with only a few discussing both, and even fewer discussing all three. Good ventilation eliminates heat from a building, daylight offers a heat source for thermal radiation, and both the wind and lighting environments cooperate and relate to each other by influencing the thermal environment, so they should be explained together. While the physical environment of a building is an interconnected environment, and several environmental factors can affect how comfortable it is. Heat, lighting, and wind all affect the comfort of living, and a single comfort of the thermal, lighting and wind environments does not reflect a better living environment, thus, the three themes should be explained together to effectively and correctly use the comfort of a building.

2.5. Conclusion of literature review

The climate adaptation of buildings defines as the characteristics and capacity of buildings to adapt to the climate. The issue of excessive energy consumption in modern buildings can be resolved by research into the adaption of old buildings. The climate adaptation strategies of traditional buildings have been researched in multiple regions, and such studies jointly reflect that traditional buildings include climate adaptation strategies and wisdom that can be considered to decrease energy consumption in traditional buildings and construct of modern buildings, and that the research on climate adaptation strategies in traditional buildings is important to the sustainable development of buildings.

The previous study has explained climate adaptation strategies for traditional buildings more qualitatively and from a more macro viewpoint, with limited analysis on certain cases of traditional buildings, but an increasing number of researches are starting to evaluate the effectiveness of climate adaptation in certain cases. The current state of research on climate adaptation strategies for traditional buildings is that more research gives focuses on the enhancement of traditional buildings and less on the effectiveness of climate adaptation strategies, mainly for traditional buildings in the Zhejiang region of China, where research is quite restricted. Moreover, several studies on the assessment of the comfort of traditional buildings normally consider a single aspect or two aspects, and there is little research on the physical environment of buildings with regards to a comprehensive assessment of the thermal, lighting, and wind environments, but the thermal, lighting and wind environments of buildings collaborate with each other, and studying only one or two aspects cannot comprehensively evaluate traditional buildings. Although Yan's courtyard complex, a structure in Zhejiang, has successfully preserved its original character, the building's current study is insufficient, and in particular, no research has been done on its comfort and climate adaption measures.

2.6. Research gap

Based on the available research on the climate adaptation techniques of traditional residential buildings, this dissertation claimed that there is still a requirement for detailed case studies on the effectiveness and cultural connotations of architectural climate adaptation techniques, which hold significance to the existing architectural design and the conservation of traditional buildings. The Yan's courtyard complex in Ningbo, Zhejiang province, was picked as a case study to close the gap in the lack of research on climate adaptation solutions for traditional structures in the area, which are well protected and whose climate adaptation strategies have not been researched in the past. This dissertation assesses the climate adaptation techniques of Yan's courtyard complex in a qualitative and quantitative way, and offers an in-depth evaluation of the thermal, wind, and lighting environments of the buildings, providing a more comprehensive evaluation of the effectiveness of climate adaptation strategies. Moreover, this dissertation evaluated the idea of the unity of man with nature and explained their relationship with climate adaptation strategies, filling a gap in the few studies that have explained the relationship between culture and climate adaptation strategies, leading to a better understanding of the sustainable development of housing.

3. Research methodology

3.1. Introduction

Traditional courtyard houses are key historical and cultural heritage, and also consist of strategies for adapting to the climate; they are important for the sustainable development of modern architecture. Traditional courtyard houses in Ningbo have developed regional architectural characteristics during the process of adapting to the local culture and climate, and Yan's courtyard complex exhibits these characteristics. This study uses the complex as an instance, proposes climate adaptation strategies adopted by the complex, and verifies their efficacy, providing cultural and climate adaptation solutions for the sustainable development of modern architecture. The local natural and cultural environments must be taken into account in climate adaptation strategies. As a result, this dissertation applies a methodological framework that includes literature research, field investigation, field monitoring, and computer simulation. First, literature research was carried out to outline the weather conditions in Ningbo, the philosophical idea of the unity of man with nature , along with the typical climate adaptation strategies of traditional architecture. Following that, field research was performed to collect architectural characteristics and dimensional data on the buildings of Yan's courtyard complex. Besides, temperature and humidity data were collected in January and July for three of the traditional buildings, which are Yan’s ancestral hall, Yan's former residence, and Yan's public granary, in the case of Yan's courtyard complex in Ningbo. In addition, a computer model of the building was developed on the basis of the collected information, and the thermal, lighting and wind environments of the building were simulated based on Ecotect software for various climate adaptation strategies in January and July for understanding the effectiveness of the Climate adaptation strategies of the building. Finally, a summary of the climate adaptation strategies of traditional buildings is presented and some adaptation strategies are suggested to increase the comfort of traditional buildings.

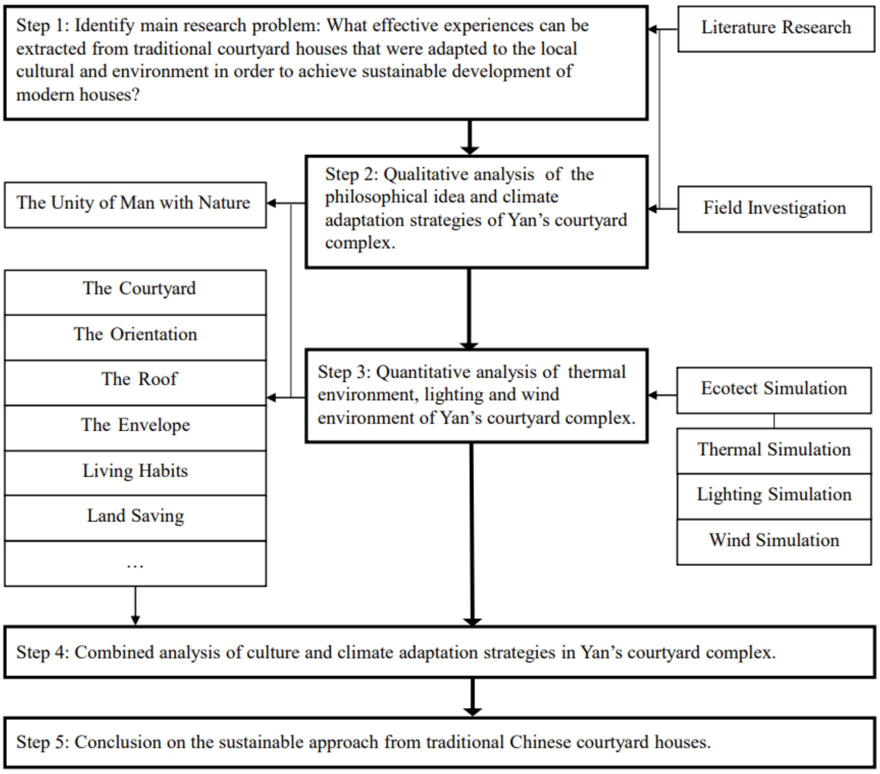


Figure 3-1. Detailed methodology of the research.

3.2. Research method

The research reviewed thesis, journals, local records, and related books focused on three main areas: (1) qualitative analysis based on literature research and field investigation, and (2) quantitative assessment of Yan's courtyard complex by field monitoring as well as software simulation.

3.2.1. Literature research

The selection of the literature was centred on three primary aspects： (1) the local climatic conditions in Ningbo; (2) traditional Chinese concepts, in particular the concept of the unity of man with nature; (3) the climate adaptation strategies of the traditional architecture, particularly in areas with a hot summer and cold winter and humid climate similar to that of Ningbo's.

Traditional structures with distinctive cultural characteristics are not the results of conscious human design; rather, they are the result of social processes that depend on the culture, environment, and society in which they are found (Orehounig and Mahdavi, 2011). Ancient craftsmen and builders who respected the local culture and the natural environment, developed ancient and simple sustainable techniques appropriate for local architecture, i.e., Climate adaptation strategies, in order to enhance the living environment and adjust the local natural conditions. The local physical surroundings, concepts of the natural environment, and ways of thinking implicitly impact the existence and growth of climate adaptation strategies, ultimately getting a positive two-way interaction between culture and technology, and building culturally and environmentally appropriate architecture.

Information on the local climate, culture, and economic levels of Ningbo along with the construction strategies and materials considered in traditional buildings, is beneficial to gain a preliminary understanding of the climate adaptation techniques of traditional buildings.

A review of literature and weather data gathered information on the physical conditions in Ningbo, including its geographical location and physical parameters related to local building design (such as local temperature, humidity, wind direction, rainfall, and other climatic parameters). Such climatic parameters can support us in analysing local climatic characteristics and extremes and exploring key objectives for the design of local building climate adaptation techniques for Ningbo's climatic conditions.

This dissertation mainly gives focus to the impact of the traditional Chinese philosophicalidea of the unity of man and nature on climate adaptation techniques. The unity of man and nature explains the Chinese philosophy of the relationship between man and nature, defined as the balance between heaven, earth, and man. Such an idea of living in harmony with nature is showcased in architecture that respects and adjusts to the local environment, which is aligned with climate adaptation techniques.

Ambient climate adaptation techniques are the adaptation of buildings to the local climate to enhance building comfort. There are a few regional characteristics of climate adaptation techniques, but there are also a few commonalities. Understanding a variety of regional climate adaptation strategies will support the exploration of local climate adaptation strategies in Ningbo.

3.2.2. Field investigation

Through field research of Yan's courtyard complex and its surroundings, a preliminary understanding of the existing situation of Yan's courtyard complex was received, containing the geographical location, building plan layout, building orientation, building materials, the current use of the buildings, and the visual perception of building comfort with an aim to qualitatively summarize the climate adaptation techniques considered in Yan's courtyard complex. Moreover, data on the building, courtyard, door, and window dimensions of Yan's courtyard complex were determined which was later utilised in the structures' computer modelling.

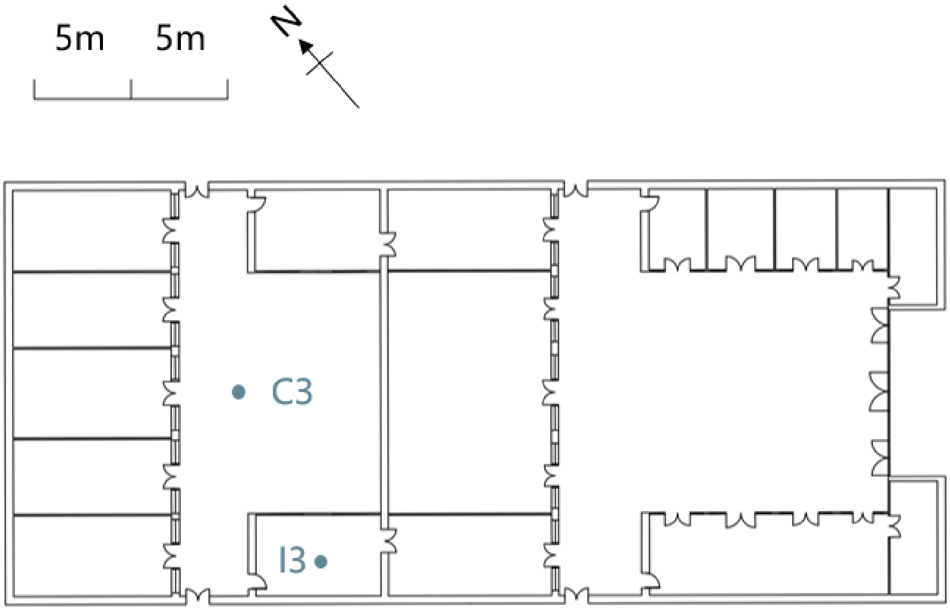
The information received by the materials review was constrained and did not allow for comprehensive information on the study's subject, and the field investigation only enabled a basic comprehension of the existing state of the building and the Climate strategies considered in the building; these two methods only allowed for qualitative analysis. In order to conduct a quantitative analysis of the physical environment of a building, a combination of other techniques was needed.

3.2.3. Field monitoring

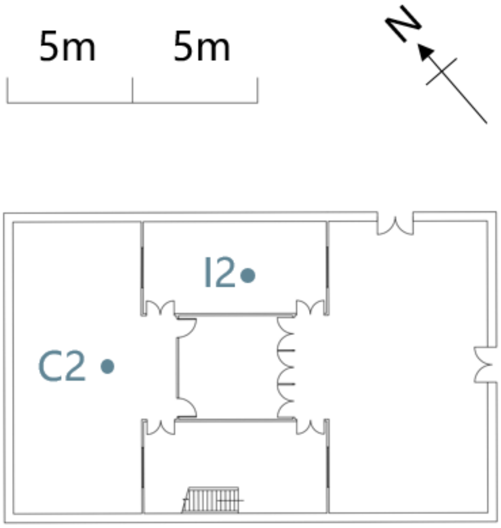
Field monitoring, considering data to visually detect the actual thermal environment of a building, is a widely considered research method where the physical environment of a building can be researched qualitatively, but also with some potential for inaccuracy owing to environmental factors, etc.

Monitoring of the temperature and humidity situations in Yan's courtyard complex during the cold and hot seasons was considered to assess and evaluate the features of the thermal environment in the courtyard and indoors. The experiment was chosen for five days of experimental monitoring in January and July. Because they are regarded as the coldest and warmest months of the year in Ningbo, respectively, January and July were chosen. The coldest month monitoring data were received between 6 January and 10 January 2022. The monitoring data for the hottest month were received between 14 July and 18 July 2022. The Yans' prior home was not tested because air conditioning external units were installed in the courtyard in the back, which could have tainted the experiment's findings. The outdoor temperature and humidity data were considered from climate data for the corresponding date at Ningbo Lishe Airport (Raspisaniye Pogodi Ltd, 2022), around 9km from Yan's courtyard complex.

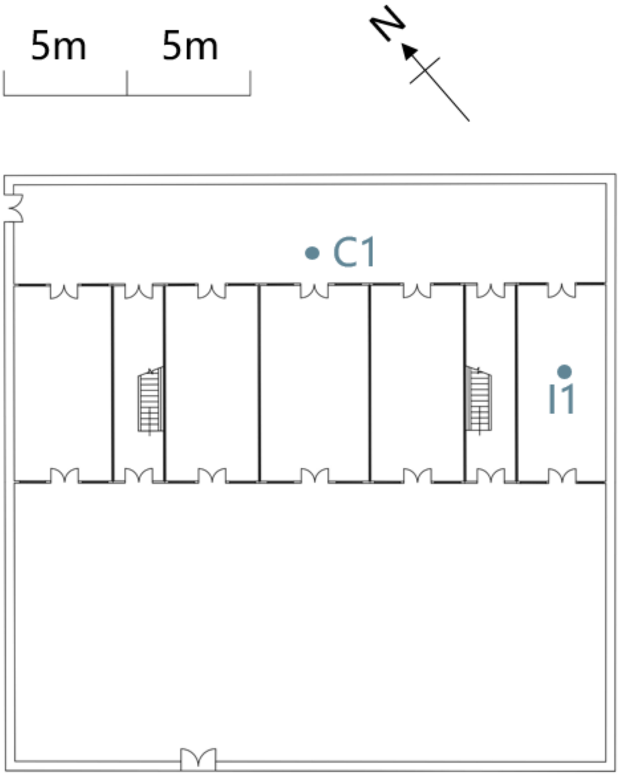
The measured parameters included contained air temperature and relative humidity, and the instrument used considered for the measurements was the smart meter TP500, which has an accuracy of ±0.5°C for temperature and ±3% RH for humidity, and the instrument complies observes with the relevant related regulations rules of ISO 7726. Based on the recommendations of ISO 7726 (*Bs En Iso 7726:2001: Ergonomics of the Thermal Environment. Instruments for Measuring Physical Quantities*, 2002), indoor air temperature and humidity are measured computed at head level (1.1 m height) of a seated person. The temperature and humidity recorders in the courtyard were placed mainly primarily positioned in the shade of the eaves to avoid prevent the effects impacts of direct sunlight on the accuracy of the measured data, at a height of 1.5m. The temperature and humidity in the courtyard and room of the three courtyard buildings were measured used to measure separately and the automatic data recording interval of the instrument was around 30 minutes. None of the measuring spaces had the air conditioning running during the measurement time. During the measurement period, no air conditioning was used in any of the measurement spaces. The three buildings are equipped with air conditioning and the rooms tested were unoccupied and empty, in order to avoid prevent the influence of the occupants' use usage of the air conditioning on experiment results. The first floor was not tested due to the first floor, which is mainly primarily used considered as office space, is constantly using air conditioning. Throughout this dissertation, abbreviations are used and considered to represent for representing a variety of spaces being tested, i.e., C1, C2, C3, I1, I2, and I3.



a. Yan’s ancestral hall.



b. Yan's former residence.



c. Yan's public granary.

Figure 3-2. Location of temperature and humidity recorders in buildings.

3.2.4. Software simulation

To further evaluate the influence of several techniques on Yan’s courtyard complex, this dissertation considered a computer environment simulation to simulate the thermal, lighting, and wind environments of the building for various techniques. Software simulations allow rapid analysis of wind, heat, and light conditions in buildings to get more accurate and richer data, building for the lack of field monitoring data or an inability to conduct field monitoring. Research into computer environment simulation dates back to the middle of the 1960s (Shao *et al.*, 2020) and it is currently frequently applied to the design and construction of buildings. Ecotect is a computer simulation and analysis software formulated by Autodesk for the comprehensive analysis of thermal, lighting, wind, and other significant building environments. Ecotect software can segregate the user-selected analysis object into uniformly sized grids and conduct uniform computations with the results displayed uniformly on the analysis grid in different colours based on the size of the values. In contrast to other simulation software, it has the advantage of easy modelling, a clear interface, and intuitive results. The general process of Ecotect simulations is to initially import meteorological data, create the model, set up the grid, conduct simulation analysis, and create graphs and data conclusions. Many researchers have used Ecotect software to evaluate the physical environment of buildings in their studies (Anh-Tuan *et al.*, 2011; Nasibeh *et al.*, 2011; Yang *et al.*, 2014a). Several studies have demonstrated the effectiveness of Ecotect (Vangimalla *et al.*, 2011).

This research uses Ecotect software as a simulation tool for the following reasons: Ecotect software is easy to operate, and for relatively complex models as Chinese ancient buildings, Ecotect software's can reduce the complicated modelling process, save modelling time and increase the editability of the model. Ecotect is a highly visual building simulation software that enables a visual and quantitative assessment of the physical environment of a building. This research uses the Solar Access Analysis, Lighting Analysis, and Winair modules in Ecotect to quantitatively visualise the shading, natural lighting and ventilation of the Yan’s courtyard complex under different climate adaptation strategies in order to analyse the physical environment of the Yan’s courtyard complex and the effectiveness of different climate adaptation strategies.

This research considered the computer simulation software Ecotect to model Yan’s ancestral hall, Yan's former residence, and Yan's public granary in Yan’s courtyard complex. The influences of several climate adaptation techniques on the thermal, lighting, and wind environments of the buildings were simulated, containing a variety of building plan layouts, courtyard widths, eaves widths, orientation, and ventilation patterns. The variables simulated contain solar radiation, illuminance, daylighting factor, wind velocity, and wind direction.

In order to examine the thermal, light, and wind environments of Yan’s courtyard complex, we considered TMY climatic data for Dinghai from Energy plus. These data were collected from the China Standard Weather Data (CSWD). The database of Energy plus does not have climate data for Ningbo and the weather parameters available are missing, therefore, the weather parameters for Dinghai, which is around 60 kilometres away from Yan's courtyard complex, were selected as climate data.

In this research, the former residence of Yan's ancestral hall, Yan's former residence, and Yan's public granary were all modelled in Ecotect. As the thermal performance of the load-bearing structures of the buildings is not examined in this research and such structures include a low impact on this study, the load-bearing structures like columns and bucket arches were not modelled. In order to discuss climate adaptation strategies for local traditional buildings, the front courtyard of Yan's public granary was modelled as a complete rectangle, which is the typical courtyard form for traditional buildings. The front courtyard of Yan's public granary is not currently a complete rectangle.

This research performed an investigation on three climate adaptation strategies of building plan layout, courtyards widths, and eaves widths and the following experimental design techniques were considered.

(1) Building layouts

Yan's public granary, Yan's former residence, and Yan's ancestral hall are all traditional buildings with different layouts. By building as black and courtyard as white, the layout of the three buildings was reflected in Figure 3-3 below, and it can be reflected that the three buildings have clearly distant floor plans, with the public granary holding a linear layout plan, the former residence a T-shaped plan, and the ancestral hall an 8-shaped plan.

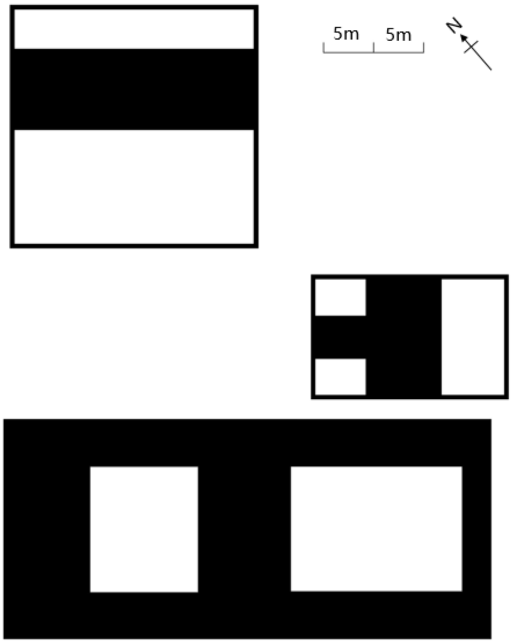


Figure 3-3. Building layout sketch.

Simulation of the three buildings separately allows the assessment of the influence of the building plan layout on the comfort of the buildings.

(2) Courtyard widths

In order to investigate the effect of courtyard widths on building comfort, simulations of courtyards with various width-to-length ratios were carried out without altering the height of the walls and buildings surrounding the courtyard of the public granary. This study will be performed as a set of simulations varying the dimensions of the courtyard in the north-east and south-west directions from 4m to 11.5 m at 1 m intervals, i.e., 4m, 5m, 6m, 7m, 8m, 9m, 10m, 11m, while keeping the width of the building constant.

(3) Eaves widths

In this dissertation, the dimensions of the eaves close to the side of the building are described as the length, and the dimensions of the eaves perpendicular to the side of the building are referred to as the width. A public granary was used as a model to simulate the impact of various widths of the first-floor eaves and second-floor eaves separately on building comfort.

The eave width of Yan’s public first floor of the granary is 1.1m while 2.38m is the eave width of the second floor. Two sets of simulations were employed in this study. The first set involved varying the eave width of the first floor pick out from 0m to 3m at 0.5m intervals, i.e., 0m, 0.5m, 1m, 1.5m, 2m, 2.5m, 3m, with the same eave width on the second floor of the public granary; another group was simulated by varying the width of the eaves of the second floor from 0 to 3 m at 0.5 m intervals, i.e., 0 m, 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, while keeping the width of the eaves of the first floor of the granary unchanged.

a. Thermal environment simulation

To acquire indoor and courtyard thermal data for the three buildings with different floor plans, courtyard widths, and eaves widths, the "Solar Access Analysis" module of Ecotect software was employed for calculating the solar radiation in the interior and courtyard of the buildings.

The simulations are carried out during the period 0:00-24:00 in January, the coldest month, and July, the hottest month of a typical year. During these times, the average daily solar radiation values, as well as the average daily mean solar radiation value, were calculated for the building courtyard and the interior of the building respectively. In Ecotect, the following is the meaning of both of them:

The average daily solar radiation value is the sum of all solar radiation in a certain grid, divided by the number of days the analysis was run, resulting in a daily average. The average daily mean solar radiation value is the sum of the average daily solar radiation values for all calculated grids, divided by the total number of calculated grids to get the average result.

b. Lighting environment simulation

For the purpose of obtaining the indoor lighting environment data of the three buildings with different floor plans, courtyard widths, and eaves widths, the "Lighting Analysis" module of Ecotect software was used to compute the indoor daylight factor and illuminance of the interior of the three buildings in CIE standard overcast sky model, with only side lighting in the rooms. The CIE standard overcast sky model is popularly used in testing the lighting settings of buildings since it is simple and easy to use, which allows the simulation of natural lighting in building interiors under the most negative weather conditions. However, its daylight factor does not reflect the effect of building orientation and location on natural light. According to the *Standard for DayLighting Design of Buildings* GB50033-2013 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013), Ningbo is a Class IV light climate zone, thus the design illuminance of outdoor natural light was set at 13,500lx.

c. Wind environments simulation

Due to the fact that Ecotect cannot directly simulate the wind environment, the WinAir plug-in in Ecotect was used in this study to simulate the wind environment around the building and in the building courtyard for different building layouts, courtyard widths, and eave widths. The dominant wind direction in Ningbo in winter is north-west and in summer is south-east, hence the wind directions in both winter and summer are north-west and south-east respectively in the simulations. The effect of opening windows and doors on the wind environment is disregarded in the simulation because the settings for the window opening type cannot be set in Ecotect. To ensure the accuracy of the simulation results and prevent errors caused by chance results, the number of air iterations was set to 1000 or more.

4. The Yan's courtyard complex

4.1. Introduction

In addition to preserving local history and culture, the traditional courtyard houses in Ningbo serve as examples of how structures may be adapted to their environment. Ningbo has a well-developed water system with many rivers, and buildings are often arranged adjacent to water. The buildings in Ningbo are mainly of wood construction as the main load-bearing structure, with brick walls as the envelope. The traditional dwelling form in Ningbo is predominantly a courtyard building with higher walls or buildings enclosing a courtyard. The reasons for this form are closely related to the climatic conditions in the area as well as to the importance placed in China on family connections. The courtyard supports ventilation, preventing dampness and lowering summer temperatures. The most significant social relationship in ancient China was the family relationship, and the traditional courtyard house was primarily resided in by the occupants of close relatives, and the enclosed courtyard traditional courtyard house came to represent families. The local traditional courtyard houses are mainly wooden structures, mostly composed of the common local fire wood, with blue bricks as the external wall material. The traditional courtyard houses are close together and the lanes between the traditional courtyard houses are small in spacing, with higher walls and narrow lanes being typical of traditional courtyard houses in Ningbo. These comparable architectural elements are also present in the Yan’s courtyard complex.

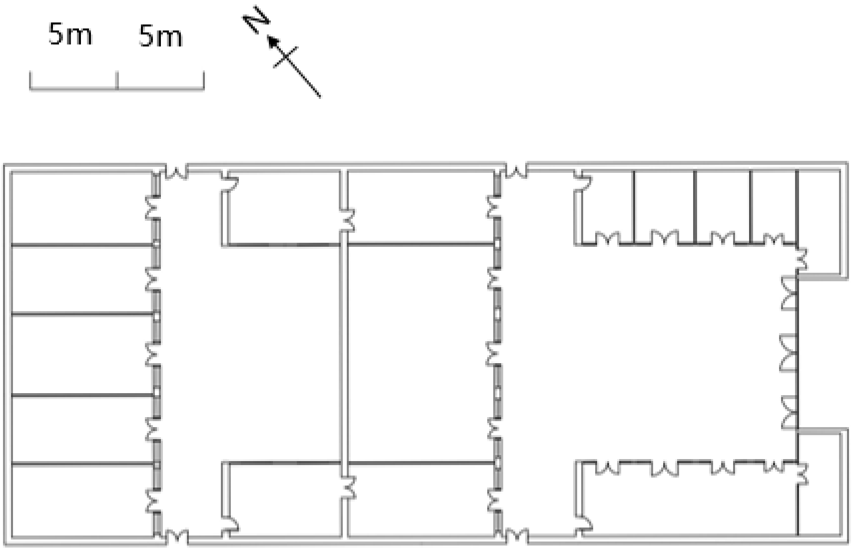
The Yan’s courtyard complex was constructed in the early Republic of China with the financial support of Mr. Yan Kangmao, a well-known representative of the "Ningbo Fellowship". Yan’s courtyard complex now contains Yan's ancestral hall, Yan's former residence, Yan's public granary, and Yan's public village, which has a total area of 4,561 square meters and a total construction area of 2,088.5 square meters. Yan’s courtyard complex now acts as office space and a park open to the public for the charity complex, Ningbo Shanyuan.

The Ningbo Fellowship Museum (2017) has performed research on the architectural exterior stylistic features, internal structural features, and plan layout of Yan's former residence, Yan's public granary, and Yan's ancestral hall, reflecting that all these buildings have a specific historical background and cultural value. Gu and Ye (2014) summarized certain construction strategies for repairing Yan's courtyard complex, with an aim to restore the complex to its original condition and encompassing its age limit and giving a beneficial reference for the conservation and repair of local traditional buildings. In his book 'Gathering and Spreading Wealth in Modern Ningbo Mr. Yan Kangmao, Sun (2016) explained the construction history of Yan's former residence, Yan's public granary and Yan's ancestral hall, their architectural features and their functions at the time, and by these studies assesses the reasons why Mr. Yan Kangmao, the builder of Yan's former residence, conducted good deeds. Few researches have been performed on Yan's courtyard complex with a focus on the architectural features, the culture behind them, and the evaluation of the conservation and restoration of the buildings. No researches have evaluated the climate adaptation strategies or the indoor comfort of Yan's courtyard complex.

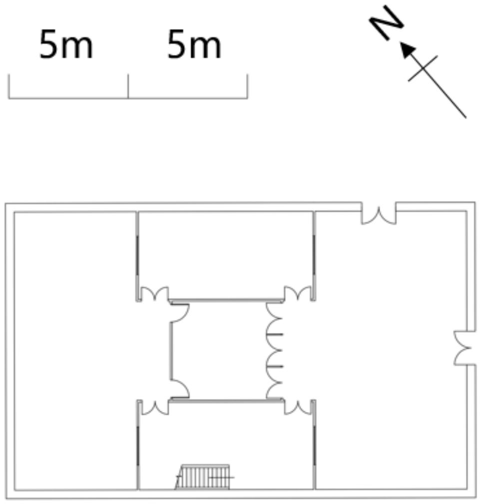
The Yan’s courtyard complex was selected as a case study, as it has typical features of traditional Ningbo architecture, retained its original architectural shape and spatial distribution, the richness of its architectural plan forms, and the presence of specific research gaps. The Yan’s courtyard complex has the main features of traditional local architecture, it is built next to the water and consists of three typical courtyard buildings combined with a narrow width of streets between the buildings. The Yan’s courtyard complex is mainly a wooden building with brick walls as the envelope. The courtyard is the main outdoor space for the users and has the role of ventilation, moisture control and increased daylighting. The exterior walls of the building do not open to the outside, and the relatively closed inner courtyard is designed to maintain the privacy of the family's internal activities. With adequate planning and collaboration, Yan’s courtyard complex was conserved in its original site. During the restoration procedure, Yan’s courtyard complex kept its original form, made extensive usage of materials from the past for restoration, and kept a good original appearance. Yan’s courtyard complex holds a variety of plan forms within a relatively concentrated space, which supports comparative research into the effect of different building builds on architectural comfort. There are few studies evaluating Yan’s courtyard complex and previous researches have not examined the climate adaptation techniques of Yan’s courtyard complex. As, there is little documentation available on the Yan’ courtyard complex, and restricted access to pre-restoration information on the complex by interviews with staff, this research relied on the existing state of the restored Yan's courtyard complex, along with documentation of similar traditional buildings.

4.1.1. Research objects

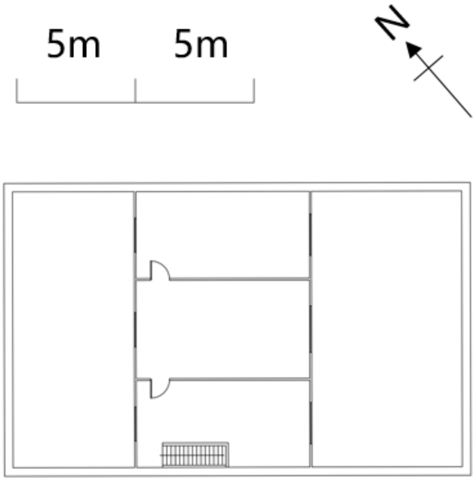
Yan's ancestral hall, Yan's former residence, and Yan's public granary were selected as the primary study objects, reflecting the three different forms of traditional Chinese courtyard architecture. The Yan’s Ancestral Hall is a quadrangular courtyard with a single-story building that faces east, with a length of 10.960 meters and a width of 10.680 meters in the first courtyard, and a length of 10.960 meters and a width of 7.375 meters in the second courtyard. The Yan's Residence is primarily a two-story building that takes the shape of a single courtyard with a length of 11.640 metres and a width of 5.530 metres. It is situated in the west facing east. The Yan's public granary is a single courtyard, facing south, mainly a double-story building, with the length of the first courtyard being 19.820 meters and the width being 9.070 meters, and the length of the second courtyard being 24.380 meters and the width being 1.870 meters.



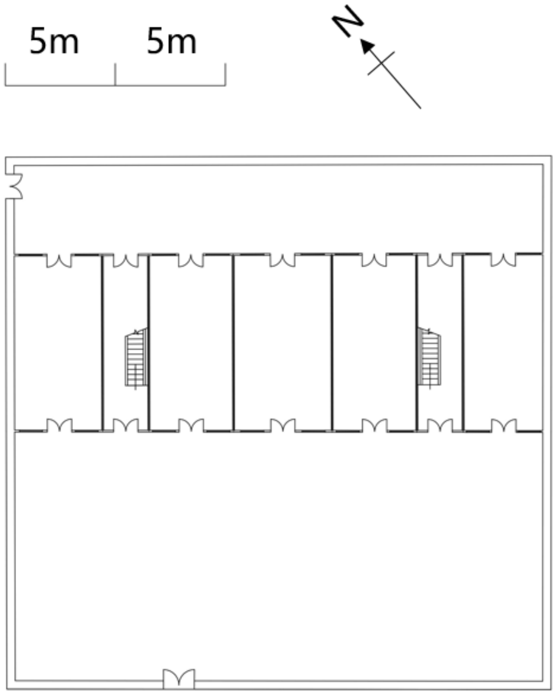
a. First floor of Yan’s ancestral hall.



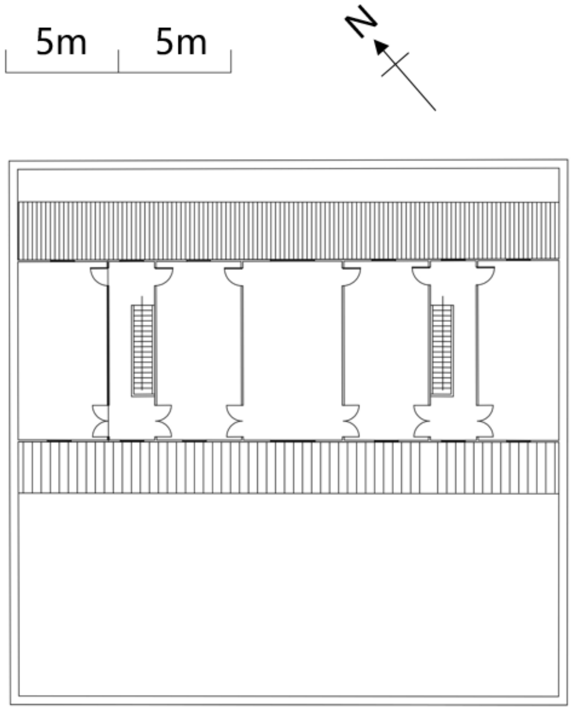
b. First floor of Yan's former residence.



c. Second floor of Yan's former residence.



d. First floor of Yan's public granary.



e. Second floor of Yan's public granary.

Figure 4-1. The plan of Yan’s ancestral hall, Yan's former residence and Yan's public granary.

4.2. The location

The Yan's courtyard complex is situated at the intersection of Guangdehu South Road and Taikang West Road in Yinzhou District, Ningbo, Zhejiang Province, China, surrounded by a rich waterway system. Zhejiang is situated on the south-eastern coast of China and the southern part of the Yangtze River Delta, bordering Shanghai, Jiangsu, Anhui, Fujian, and Jiangxi provinces. Ningbo is situated on the Ningbo Plain in the eastern section of the Chinese province of Zhejiang. Ningbo has a significant history that dates back as far as 7,000 years ago to the Hemudu culture. Ningbo is a significant port city in China and has become a leader in the economic and cultural fields since the Song and Yuan dynasties (Ma, 2019).

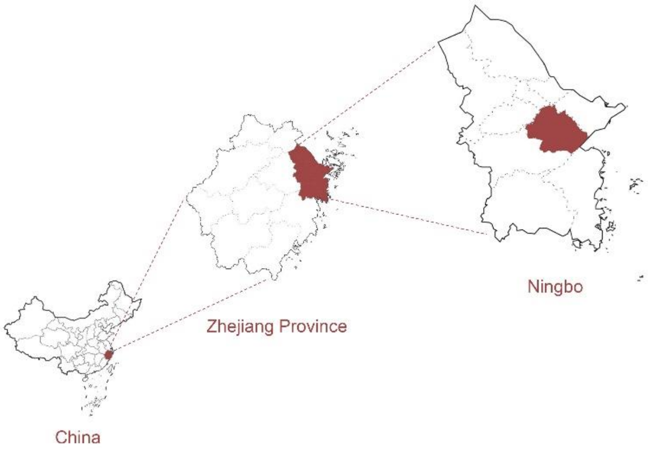


Figure 4-2. Location of the Yan’s courtyard complex.

Figure 4-3. Location of Yan’s courtyard complex.

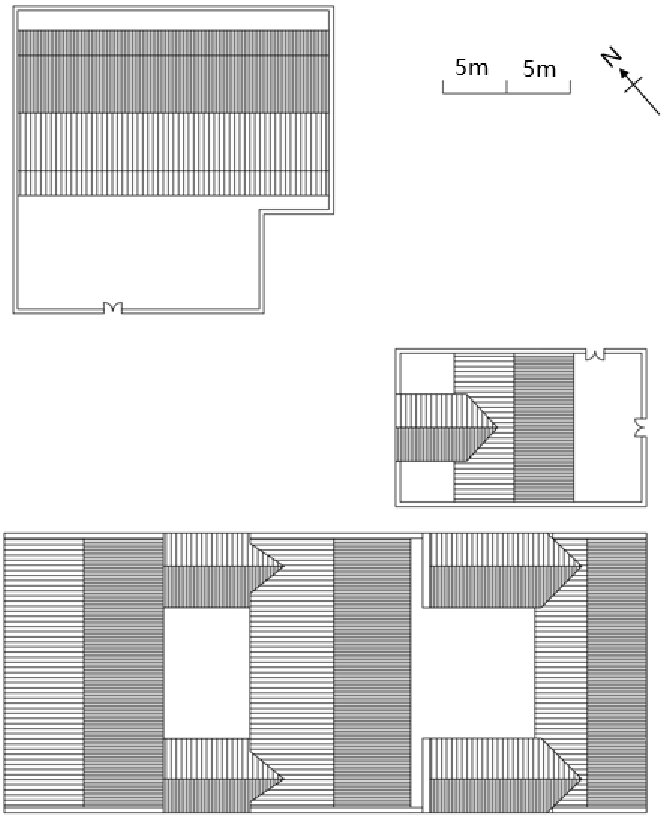


Figure 4-4. Plan of Yan’s courtyard complex.

4.3. The climate

Ningbo is located in the eastern coastal region of Zhejiang Province, China. Due to its proximity to the East China Sea, it has a subtropical monsoon climate, with maritime characteristics. The monsoon winds in Ningbo alternate significantly, with north-westerly winds prevailing in winter, and frequent alternation of cold and warm air in spring, making it prone to catastrophic weather such as gales and thunderstorms, south-easterly winds in summer and typhoons owing to the high subtropical temperatures of the Pacific Ocean, and rainy weather in autumn because of the frequent convergence of cold and warm winds. With four distinct seasons, long winters and summers, and short autumns and winters, Ningbo is part of China's hot summer and cold winter climate zone. The average annual temperature of Ningbo, according to the Typical Meteorological Year (TMY), is 13°C, with an average maximum of 21°C and an average minimum of 13°C. The average monthly temperature in winter (December-March) ranges from 3°C to 11°C. January is the coldest month, with average daily temperatures ranging from 2°C to 9°C. The average monthly temperature in the summer (May-September) ranges from 24°C to 32°C. July is the hottest month and has average daily temperatures of 32°C to 25°C. The climate in Ningbo is moderate and humid. Rainfall is abundant, primarily from May to September, and the typhoon season is from May to October each year due to the abundance of water vapour carried by the southeast and southwest monsoons blowing from the Pacific and Indian Oceans. The climate is mild and humid, with abundant rainfall and an average annual relative humidity of 77%.

4.4. Building climate elements

The climate adaptation strategies in traditional buildings aim to improve building comfort, which is mainly evaluated by the building climate elements, such as air temperature, air humidity, thermal comfort, solar radiation, light levels, light coefficients, and wind velocity.

4.4.1. Air Temperature

In meteorology, the physical quantity that indicates the degree of hot or cold air is referred to as air temperature. Temperature is an important parameter in determining comfort. The most intuitive perception of the climate is dominated by the air temperature, and too high or too low a temperature can have an impact on people's perception of comfort and even on their health.

4.4.2. Relative humidity

Humidity is a measure that determines how dry or wet the air is, or how much water vapour is contained in the air. The relative humidity is usually utilised to measure the amount of humidity in the air, which is the ratio of the actual water vapour pressure in the air to the saturation water vapour pressure at the prevailing temperature. People are more likely to feel hot in the summer and cold in the winter in locations with high relative humidity; on the other hand, in areas with low relative air humidity, people feel more comfortable than in areas with high humidity.

4.4.3. Thermal comfort

Thermal comfort is an essential factor in determining a building's thermal environment. Lucia Castaldo et al. (2017) pointed out that indoor thermal comfort is the most significant factor affecting the comfort of the indoor environment. Heat balance and adaptive models are two popular thermal comfort models that are often used to calculate the thermal comfort of buildings. Heat balance models are developed using laboratory data and are more suitable for buildings with mechanical temperature control, while adaptive models are primarily based on field study data and are appropriate for evaluating buildings with natural ventilation (Yang *et al.*, 2014b).

Thermal comfort is defined in ASHRAE Standard 55 as " the state of mind that expresses satisfaction with the thermal environment " (Firm, 2013). Thus, cultural, psychological, and behavioural influences as well as physiological factors can affect thermal comfort(Mirrahimi *et al.*, 2016) The adaptive model assumes that people are able to adapt to the thermal environment through behavioural adjustments, loosening expectations and adapting to the conditions they are exposed to (Frontczak and Wargocki, 2011). Occupants often restore comfort by adding and removing clothing and opening and closing windows (Yüksel *et al.*, 2021). The adaptive model attaches great emphasis to the cultural, social, and behavioural aspects of the user, and the approach feels comfortable in a wider range of conditions than the criteria suggested by the thermal balance model (Vitale and Salerno, 2017). This dissertation studies naturally ventilated conventional buildings. Adaptive thermal comfort is the main model employed to investigate thermal comfort in naturally ventilated buildings, so the adaptive model is used in this dissertation for assessing the thermal environment of the building.

According to the adaptive thermal comfort model, the indoor thermal comfort temperature is determined based on the outdoor temperature. The equation is as follows:

$$T_{comf} = A + BT_0 \tag{4-1}$$

T_{comf} is the comfort temperature (°C); To the monthly average outdoor air temperature (°C); and A, and B are constants. The constants A and B are determined by climate region and cultural context.

The following is the relationship between the thermal comfort temperature and the monthly mean outdoor temperature in China (general):

$$T_{comf} = 19.70 + 0.30T_0 \tag{4-2}$$

According to ASHRAE 55, two percentages of satisfaction are taken into account, one for 80% acceptability and one for 90% acceptability. 80% acceptability applies to typical applications and 90% can be utilised when a higher standard is required. 80% amplitude range is 7°C while 90% satisfaction is 5°C amplitude range. 80% acceptability has been employed in this investigation.

4.4.4. Solar radiation

The electromagnetic waves and particle streams emitted by the sun into cosmic space are referred to as solar radiation. Solar radiation is thought to be the main source of heat gain, increasing the heat generated by human metabolism due to its occupancy characteristics. Due to the solar radiation they receive, buildings overheat in the summer and increase their temperature in the winter.

4.4.5. Daylighting factor and illuminance

The natural lighting effect of a building is usually assessed in terms of illuminance and daylight factors. Illuminance denotes the amount of light flux passing through a unit area in the working plane. The daylight factor is described as the ratio of the level of internal light to the level of outside light under a standard fully overcast sky. The daylight factor is a concept that is used in the context of a typical sky model and, despite being inevitably restrictive, continues to be crucial in modern architecture because it provides a clear and concise portrayal of the problems associated with the natural lighting of buildings. A good lighting environment improves the efficiency of the occupants' work and life. Since sunlight is the primary source of light in traditional buildings without mechanical lighting and the illuminance and light factor obtained by sunlight in buildings is very limited, so the lighting environment in traditional buildings needs to have higher illuminance and daylight factor.

4.4.6. Air velocity

The wind is the horizontal movement of the atmosphere caused by differences in atmospheric pressure in nature. Air velocity is the rate of movement of air with respect to a fixed location on the earth. Good ventilation can effectively promote indoor heat exhaustion while improving the building's indoor environment. Different air velocities bring different levels of comfort to the human; too high a velocity can be dangerous, and a prolonged lack of indoor air circulation can be uncomfortable as well.

4.5. Climate adaptation objectives for traditional buildings in Ningbo

The principle of climate adaptation in traditional architecture is to take advantage of the climate in terms of site selection, layout, and building materials, with the goal of coping with adverse climatic conditions and creating a comfortable environment for the users, based on a thorough understanding of the local climate and natural environment (Wang, 2021). This implies that there is a strong relationship between local climate and the climate adaptation strategies of traditional buildings. Therefore, this study discussed the following climate adaptation objectives depending on the local climate and user comfort in Ningbo, as well as taking into account the regional aspects of traditional building construction, in order to better understand climate adaptation strategies.

4.5.1. Heat protection in summer and cold protection in winter

The temperature has the biggest influence on how comfortable a building is since either too high or too cold temperatures affect people's health. Due to the fact that the climate of the

Ningbo region is characterised by cold winters and hot summers, buildings in the region need to be ventilated and cooled in the summer and kept warm in the winter. Solar radiation is the main source from which buildings obtain heat from nature. Radiant heat transfer consists of two aspects, the direct transfer of heat from solar radiation to the building, and the transfer of radiant heat between the internal surfaces of the envelope and internal disturbances. The primary technical methods for affecting a building's thermal environment without the use of contemporary equipment are building orientation, shading, and envelope structure. In general, a southern orientation allows the building to take full advantage of sunlight (Yang *et al.*, 2014a). In the hot season, shading is utilised to reduce the amount of heat gained indoors, and in the cold season, shading is used to increase the amount of heat gained indoors by reducing shading. The thermal insulation of the building envelope in winter and the thermal insulation in summer have a significant impact on improving the comfort of the building's thermal environment.

4.5.2. Moisture and rain protection

Ningbo, which is located on the southeast coast of China, has a humid climate with abundant precipitation in all seasons, a long rainy season, and a tropical monsoon climate, which indicate that the region has more humidity and more rain in comparison to other hot summer and cold winter climate regions. An extended period of heavy rain can erode the foundations of buildings, increase summer humidity and winter coldness, and even be harmful to people's health. Moisture and rain protection are therefore important climate adaptation objectives for the region. The roof of a traditional building prevents rainwater from eroding the walls and a well-developed drainage system with both open and concealed gutters ensures that rainwater flowing down the roof and into the courtyard is drained away smoothly.

4.5.3. Ventilation

In addition, the different climate adaptation objectives interact with one another, as good ventilation will improve the thermal environment by lowering indoor temperatures in the summer and exhausting humid air. Ventilation is thus a climatic adaptation objective that must be taken into account while building traditional buildings. The ventilation of the traditional building is mainly influenced by the way the building is arranged, its orientation, form, and ventilation methods. In Ningbo, where south-easterly winds prevail in summer and north-westerly winds predominate in the winter, buildings that are oriented in the same direction as the local wind have superior ventilation. The installation of outdoor spaces such as courtyards will create wind pressure between them and the buildings, which in turn enhances ventilation. Natural ventilation provides advantages over mechanical ventilation in terms of saving energy, reducing pollution, and facilitating the satisfaction of human comfort (Wang, 2011). Jamaludin et al. (2014) claimed that natural ventilation is considered to be the best way to provide comfort to occupants.

4.5.4. Adequate daylighting

Building daylight conditions refer to how well it receives sunlight or sunlight shading. People's physical and mental health is improved by good illumination, which also enhances the indoor environment. In the past, traditional buildings did not have access to mechanical lighting thus, natural light sources were the main source of light for the buildings, with the sun being the major source of light. Hence obtaining more sunlight was one of the objectives of traditional building construction. The choice of climate adaptation strategy, therefore, necessitates a combination of various climate adaptation objectives.

The selection of a climate adaptation strategy is the end result of a profound analysis of the local environment and the local climate. Ningbo is a coastal city with hot summers and cold winters, and abundant rainfall in all seasons. As a consequence, heat protection in summer and cold protection in winter, moisture and rain protection, ventilation, and daylighting are the key climate adaptation purposes.

4.6. The ancient philosophical concept: the unity of man with nature

The Chinese have long admired nature, sought to live in peace with it, and desired a society in which man and nature are one. In Confucianism, heaven, earth, and humanity are considered as trinity, since humans are united with heaven, and heaven encompasses earth (Zhuang, 2015). This implies that everything in the universe, including the earth and human (heaven, earth, and man) is a whole and there is a symbiotic relationship of mutual support between them.

In contrast to Western anthropocentrism, ancient Chinese conceptions of the natural world had a different relationship between humans and the environment. Ancient thinkers believed that humans could live in the natural world, but only if they did it in harmony. The ancient Chinese view of the natural environment is to bring man and nature together rather than imposing man’s will on nature. According to Taoist philosophy, a man follows the earth, the earth follows heaven, heaven follows the Tao, and Tao follows nature. This reflects that all things hold their own laws, and man must follow the laws of the Tao; when shown in the view of the natural environment, it implies that man should follow the laws of nature and respect them. All action individuals take that disturbs the balance of the natural world eventually has an impact on their life. The transformation of nature by a human can be seen as an effort by humans to live in harmony with the natural environment (Tucker, 1991). In other words, the goal of people changing the world is ultimately to advance world peace rather than just bettering the environment in which they reside (Brasovan, 2016). According to ancient Chinese humanism, man is consistent with the cosmic order (Weiming, 2001). Any policy or practical decision must carefully consider the potential effects on one's biological and ecological existence, as well as their propensity to reproduce (Brasovan, 2016). The fundamental idea behind the ancient Chinese conception of the environment is that, in order to understand and influence nature, humans should follow the objective laws of natural development and achieve harmony and unity between human and all other living things.

The philosophical idea of "the unity of man with nature" has had a significant impact on traditional Chinese architecture's philosophy and method. The idea of the unity of man with nature reflects that in the practice of architecture, the local climate and natural circumstances should be respected in order to produce harmony between the comfort of the occupants and the environment. This idea motivated builders and craftsmen to design and build buildings that suited the local climate and surroundings, giving people a comfortable place to live. The Climate adaptation strategies embodied in traditional Chinese architecture thus showcase the continued pursuit of the ancient builders and craftsmen of the natural ecological concept of the unity of nature and man. The interaction with the surroundings was highly valued in the process of building design and construction in ancient China. For instance, in ancient China, choosing a site for a building was very important since it was believed that the natural environment had an impact on a person's destiny (Yushun, 2016). Whether the building of a capital city, a palace, or an ordinary dwelling, the first thing to do was to select a site with a better climatic and natural environment. The key requirements for selecting a site in ancient times were to hide wind, collect Qi, and get water (藏风、聚气、得水), reflecting that protecting buildings from strong winds and being close to water sources in order to get the Qi that the ancients believed was important for life (Wu *et al.*, 2012). Avoiding strong winds was a way to reduce the danger to the building and its occupants, and proximity to water sources allowed for simple access to water, which was in fact a summary of people's adaptation techniques to the climate, avoiding harm by following the laws of nature. The focus on site selection is a reflection of the ancient Chinese desire to design buildings in harmony with nature, a reflection of the ancient Chinese idea of the ecological environment in which heaven and man are combined. In short, the development of traditional Chinese architecture was highly affected by the philosophical concept of the unity of nature and man, and summed up a set of climate adaptation techniques.

4.7. Climate adaptation strategies

4.7.1. Building site selection and layout

In ancient China, greater attention was paid to the choice of site for the buildings. The Yan's courtyard complex is surrounded by water on three sides, satisfying the ancient vision of people who wanted to live by the water and have easy access to it.

The layout of traditional architecture embodies the Chinese pursuit of harmony and order. Buildings and courtyards were frequently symmetrically and evenly spaced along a central axis by ancient builders. The courtyard and buildings in Yan's former residence were also arranged along a longitudinal axis. In the case of Yan's public granary, when people walk through it, they will experience a series of spatial changes: the front courtyard, the space under the eave, the indoor living space, the space under the eave, and the back courtyard. Thus, the opportunity for people to communicate with nature is increased because they have to pass through the courtyard with wind, rain, and daylight in order to enter the indoor living space. When the indoor and outdoor spaces alternate, people's experience of nature is richer in space and their relationship with nature is more intimate. The layout of the building is in line with the ancient Chinese concept of the unity of man with nature.

4.7.2. Courtyard

The courtyard is an enclosed space surrounded by buildings, walls, and corridors. It was believed that the courtyard is the medium through which people achieve harmony with the universe. When people stand in the courtyard, as in the universe, they can access the sun, the air, the rain, and even the gods (Hu, 2008). As a result, the courtyard has become a key focus of design in traditional buildings.

The courtyard is the soul of ancient Chinese architectural layout. In traditional Chinese courtyard buildings, the courtyard's atmosphere is improved by introducing natural landscapes. On the one hand, it can soften the square space of the Chinese courtyard, and on the other hand, can improve the environment of the entire building, giving people a satisfying visual and spiritual experience. A courtyard can provide natural light, solar radiation, and ventilation for the building's internal environment (Apolonio Callejas *et al.*, 2020). Regarding natural light and solar radiation, the courtyard brings in more light and solar radiation, while the ultraviolet light from the sun inhibits bacterial reproduction. Traditional Chinese buildings usually face south so as to get more natural light and enhance people's living environment. Concerning natural ventilation, improved ventilation can improve air quality as well as cooling capacity. Courtyard buildings can generate wind through the layout of space, the air flow brought on by wind pressure difference and heat pressure difference. To sum up, besides meeting people's aesthetic and spiritual needs, the courtyard also has a critical part in improving the thermal, wind, and lighting environment of the building.

4.7.3. Building orientation

A favourable orientation affects the building's thermal comfort, ventilation, lighting, and other factors. Traditionally, the majority of buildings are facing north to south, which is a choice made by people to adapt to the surroundings. The traditional buildings benefit from this since it allows for full access to light and solar radiation as well as avoiding the cold northwest winds in the winter and welcoming the warm south-east winds in the summer. Sitting north to south is therefore a way of grasping the laws of nature, and is all about the following nature. The Yan's courtyard complex may not be facing south due to site constraints; Yan's former residence and Yan’s ancestral hall face south-east, however, the main orientation of the buildings still faces north-south.

4.7.4. The roof and the eave

Three parts make up traditional architecture: the pedestal, the body, and the roof. Each of these three parts corresponds to heaven, earth, and human. From this, it can be observed that the concept of architecture is in fact a human-created universe in the traditional Chinese concept. The roof occupies a significant position in the structure since it is the part closest to the heaven in the building, corresponding to heaven in the building.

In order to cope with the hot summers and the abundant rainfall throughout the year in Ningbo, traditional buildings in this region frequently have roofs that slope down to the courtyard. The sloping roof allows rainwater to flow down to the ground, preventing erosion of the building's body. Furthermore, the roof often extends beyond the wall of the building to create an eave, which further protects the wall of the building from rainwater erosion, while also decreasing the amount of solar radiation received by the interior in summer and the inside temperature.

The eaves of Yan's former residence extend out of the building, partially sheltering the courtyard and connecting the courtyard, which is a symbol of nature, with the interior of the courtyard house. The eaves minimise the negative effects of adverse weather conditions on the occupants, for instance by providing shelter from the rain on rainy days and from solar radiation in hot seasons. The space under the eaves also increases access to nature during bad weather. On rainy or snowy days, people can likewise enjoy the rain and snow under the eaves.

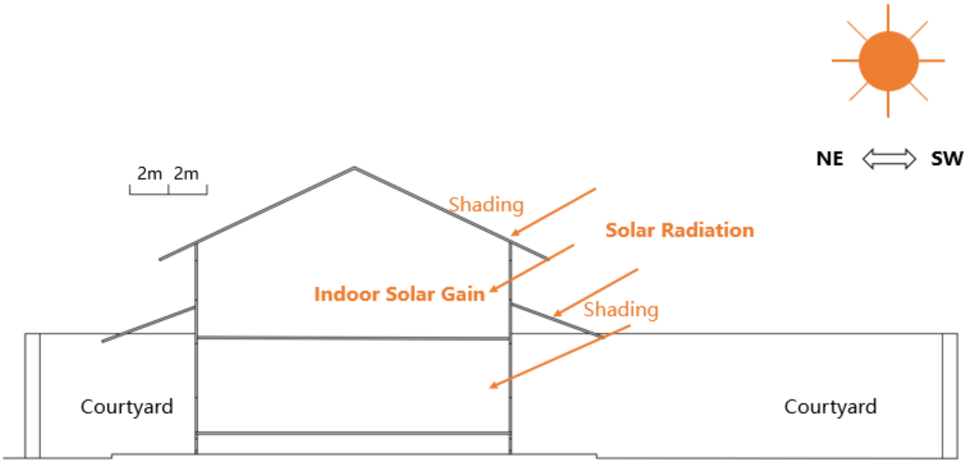


Figure 4-5. Shading diagram.

Figure 4-6. The eave of Yan's former residence.

The requirement for a thermally comfortable environment during use brings a certain amount of energy consumption in the building. From an energy-saving perspective and in order to reduce the long-term operating costs of the building, the building envelope is required to have good thermal stability, so that the indoor temperature environment remains relatively stable despite changes in the external ambient temperature, which reduces the reliance on air conditioning and heating equipment.

Thermal resistance is the physical quantity of the envelope itself or a layer of material within it that resists heat transfer. Thermal resistance is related to the thermal conductivity and thickness of the material. The greater the thermal resistance of a material, the less heat is transferred through the unit area of the material per unit time. A material's poor thermal conductivity results in less heat dissipation, better thermal insulation, and more thermal stability; less heat flows from indoors to outdoors in winter and less heat flows from outdoors to indoors in summer.

1. Equation for calculating the thermal resistance of a single material layer is as follows:

$$R = \delta/\lambda \tag{4-3}$$

where R is the thermal resistance of the material layer ($m^2 \cdot K/W$); δ denotes the thickness of the material layer (m); λ represents the thermal conductivity of the material [$W/(m \cdot K)$].

2. The following is the equation for calculating the thermal resistance of a multi-layer envelope.

$$R=R_1+R_2+R_3+...+R_n=\delta_1/\lambda_1+\delta_2/\lambda_2+\delta_3/\lambda_3+...\delta_n/\lambda_n \quad (4\text{-}4)$$

where $R_1+R_2+R_3+...+R_n$ are the thermal resistance of each layer of material ($m^2 \cdot K/W$)； $\delta 1$, δ_2, $\delta_3...\delta_n$ is the thickness of each layer of material (m)； λ_1, λ_2, $\lambda_3...\lambda_n$ denotes thermal conductivity of each layer of material [W/(m·K)].

The roof construction method used in Yan's courtyard complex calls for laying the brick for the roof on top of the wooden rafters. This is required to be laid densely without leaving too much space so as to avoid excessive gaps between the brick for the roof from causing rain leakage and moisture erosion, along with putting Chinese-style tile on top of the brick for the roof. The bricks for the roof perform the function of blocking rainwater from seeping into the interior and are useful in preventing draughts and falling dust, and they give the interior a flat roof appearance. The Chinese-style tiles effectively drain rainwater from the roof and, when arranged in an overlapping pattern, create an air gap for insulation, obstructing direct sunlight from reaching the interior during the day. Some traditional courtyard houses are also built with ash and clay on top of straw mats, and 1-2 layers of this material are laid between the bricks for roofs and Chinese-style tiles. These materials are tamped in layers for the purpose of increasing the heat insulation and waterproofing of the roof. Tile roofs have better ventilation and heat dissipation properties in comparison to modern concrete roofs, which enhances the building's thermal and ventilation performance.

Type of roof	**Material**	**Thickness, m**	**Thermal conductivity, W/(m·K)**	**Thermal resistance of the material, m²·K/W**	**Thermal resistance of the roof, m²·K/W**
The roof of Yan's courtyard complex	Chinese-style tile	0.02	0.84	0.02	0.05
	brick for roof	0.015	0.65	0.02	
The roof of other traditional courtyard houses	Chinese-style tile	0.02	0.84	0.02	0.15
	straw mats with ash and clay	0.06	0.58	0.10	
	brick for roof	0.015	0.65	0.02	

Note: Thermal conductivities are from the Thermal Design Code for Civil Building (GB5176-2016) and Yu *et al.*(2021).

Table 4-1. Thermal resistance of the roof.

4.7.5. The Wall

The majority of traditional courtyard houses in Ningbo are made of wood, with wooden columns and beams bearing the weight. Walls frequently act as an envelope and serve as thermal and heat insulators rather than being the primary load-bearing structure. In the past there was no air conditioning equipment, so the ability of the walls to insulate and keep warm would considerably affect the room's temperature, and therefore the thermal performance of the walls was one of the most important reasons for the indoor thermal environment. Depending on the material of the wall, wood panelling, blue brick, and stone are the main materials used in traditional courtyard houses in Ningbo, with wood-panelled walls and blue brick walls being more common. There are two types of blue brick walls: solid brick walls and hollow brick walls. Solid brick walls are built with layers of brick, staggered lap each other solid. Hollow brick walls are hollow walls composed of bricks laid sideways or alternating between flat and sideways. To increase the strength of the structure and its thermal insulation capabilities, some traditional courtyard houses also fill the interior of the hollow brick walls with clay or excess bricks and stones used in the construction process. The lower part of the external wall of Yan's courtyard complex near the external street is made of stone, whereas the upper part is a 38cm thick hollow brick wall, and the external wall near the courtyard and the internal partition wall is made of wood panels, generally 4cm thick. The outer walls of Yan's courtyard complex are composed of stone, which separates them from the ground so as to protect them from moisture and rain.

Type of wall	**Material**	**Thickness, m**	**Thermal conductivity, W/(m·K)**	**Thermal resistance of the material, m²·K/W**	**Thermal resistance of the wall, m²·K/W**
Wood panel Wall	Wood	0.04	0.14	0.29	0.29
Solid brick wall	Blue Brick	0.38	0.65	0.58	0.58
Hollow brick wall	Blue Brick	0.06	0.65	0.09	0.36
	Air	0.26		0.18	
	Blue Brick	0.06	0.65	0.09	
A Hollow brick wall filled with yellow mud	Blue Brick	0.06	0.65	0.09	0.74
	Yellow Mud	0.26	0.47	0.55	
	Blue Brick	0.06	0.65	0.09	

Note: Thermal conductivities are from the Thermal Design Code for Civil Building (GB5176-2016) and Wang (2014).

Table 4-2. Thermal resistance of the wall.

Table 4-2 illustrates that the thermal resistance is ranked from largest to smallest: hollow brick wall filled with yellow mud > solid brick wall > hollow brick wall > wood panel wall. As can be seen form this, the hollow brick wall filled with yellow mud has the best thermal insulation. On the other hand, wood panel wall has poor thermal insulation but good thermal performance. A comparison of the thermal resistance of hollow brick walls filled with yellow mud is much greater than that of ordinary hollow brick walls, which points out the fact that the material in the hollow brick wall cavity has a strong influence on its thermal resistance. The walls in the different locations of Yan's courtyard complex make use of a variety of materials for the function and use required. Wooden panel walls are frequently used as partition walls in buildings due to their main benefits, which include ease of construction and maintenance. Both hollow and solid brick walls are most often used for external walls close to external streets due to the fact that they are strong and durable and serve to isolate the external street and protect the living space. They have good insulation properties for the local hot summer and warm winter climate, and the blue bricks themselves are more resistant to moisture, making them excellent for usage in the local humid climate. Moreover, they have good sound insulation, avoiding noise penetration through the wall. The air layer acts as a transition between indoor and outdoor temperatures, and when the temperature difference is too great, the water vapour inside the air layer condenses and effectively insulates the humid air and keeps the room dry.

4.7.6. The window and door

The enclosed and cohesive courtyard buildings are also a product of the family system. The ancient Chinese held the opinion that there should be a strict distinction between the courtyard house and the external street to isolate occupants from the outside environment. As a result, the external walls towards the street were devoid of windows, and traditional courtyard houses only had windows that opened towards the courtyard. A deeper sense of belonging and greater family cohesion result from individuals living inside being able to perceive strangers as being separated from them on the outside and the family as being gathered and protected within.

The significance of courtyard becomes apparent when the building cannot open its windows to the outside, preventing ventilation and natural lighting. Taking the most common layout of a single building along with a courtyard in traditional courtyard houses as an instance, the comfort of the living environment is improved by opening the windows towards the courtyard and bringing light, solar radiation, and wind into the room. Through the courtyard, a balance between cultural diversity and climate adaptability has been reached. Using Yan's former residence in Yan's courtyard complex as an example, the layout of the residence is further improved by adding back courtyards to this most common form. Separating the front and back courtyards makes it possible to more clearly define the role of the courtyard, with the front courtyard being used mainly for daily receptions and entertainment and the back courtyards being used primarily for the drying of food crops and family work, etc. With the creation of the back courtyards, the building is able to open its windows to the back courtyards, thereby increasing the amount of light, solar radiation, and wind that the building receives. Moreover, indoor thermal comfort is further improved by the convection of air between the front and back courtyards.

4.7.7. The Ground

The main function of Yan's public granary was to store grain, and at the time a large amount of the stored grain was utilised for the relief of the poor (Sun, 2016). The moisture protection of the public granary was given considerable attention in order to fully exploit the function of storing grain and to avoid damage to grain caused by moisture. The indoor wooden first floor where the grain is stacked is raised 0.57m above the outdoor floor for the purpose of preventing moisture. The floor cage is not completely enclosed, and there are beautifully designed vents towards the courtyard and towards the interior of the building, as well as vents towards the interior of the building for increasing air flow under the floor and creating natural ventilation to prevent moisture.

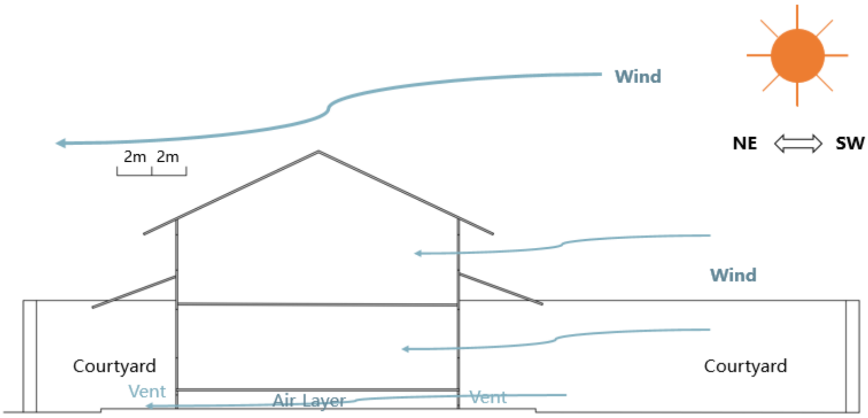


Figure 4-7. Ventilation diagram.

Figure 4-8. Yan's public granary

4.7.8. The living habits

The climate adaptability of traditional buildings is not merely reflected in the design and construction process, but also in the process of usage. When people use a building, they make active use of the environment through their own actions to achieve improved living comfort. For instance, in the summer evenings, water from the well is used to cool down the stone slabs in the courtyard, and after dinner, the family gathers there to converse and relax. When the indoor temperature is too high or too low, people will open or close the windows to improve the thermal comfort of the room. The windows in Yan's former residence have two layers, the outer wooden panel window, and the inner glass window. The two layers of windows enable people to move to choose the best possible way to open the windows. People can open or close the glass window or the wooden panel window depending on the situation, and there are hollow spaces in the wooden panel window so that even if the panel is closed, airflow through the room and air circulation is still maintained.

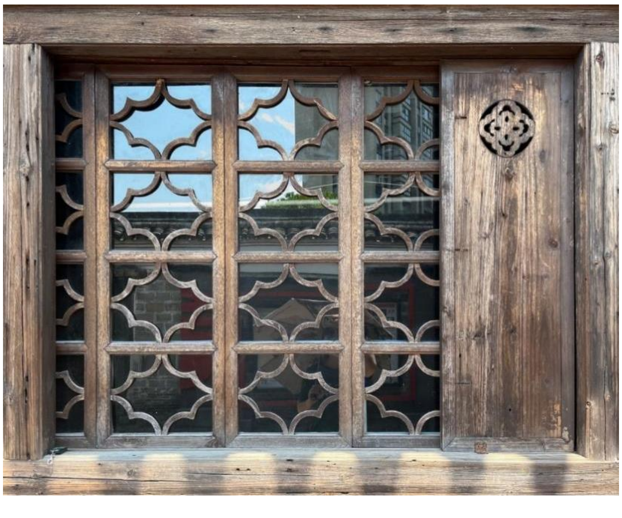


Figure 4-9. The window with two layers.

4.7.9. Water saving

Since water is a natural resource that all living creatures on earth depend on, saving water is one of the most crucial steps toward creating sustainable buildings. In buildings, there are three basic ways to conserve water: (1) water conservation, (2) water recycling, and (3) rainwater collection and utilisation. Despite the fact that traditional buildings cannot use technology to collect and utilise rainwater, there are a number of buildings that use water tanks, culverts along with other means to collect and utilise rainwater.

As well as being key for human survival, water is also a symbol of wealth in Chinese culture. Consequently, traditional buildings often tend to slope their roofs towards the courtyard, where rainwater will flow, with the intention of retaining the wealth in one's home. However, Ningbo is a city of abundant rainfall and a roof sloping towards the courtyard would cause rainwater to flow back into the interior when it rained continuously and heavily. To prevent this problem, the interior floor of Yan's residence was raised by 0.13 m above the courtyard floor, the interior floor of Yan's ancestral hall was raised by 0.10 m, while the interior floor of Yan's public granary was raised by 0.12 m. Besides, water tanks were placed in the courtyard for rainwater collection and the water in the tank can be used for both drinking purposes and also for unexpected fires. This demonstrates that the ancient builders were also capable of proposing ways of adapting to the environment to avoid conflicts between cultural pursuits and the environment. In addition, there are also drainage holes in the four corners of the courtyard floor, allowing the rainwater to flow into the holes from all sides and preventing water from accumulating in the courtyard. This suggests that water conservation and usage have been taken into account in the use and design of Yan's courtyard complex and that the design of Yan's courtyard complex has been adjusted to the rain-rich climatic conditions of Ningbo.

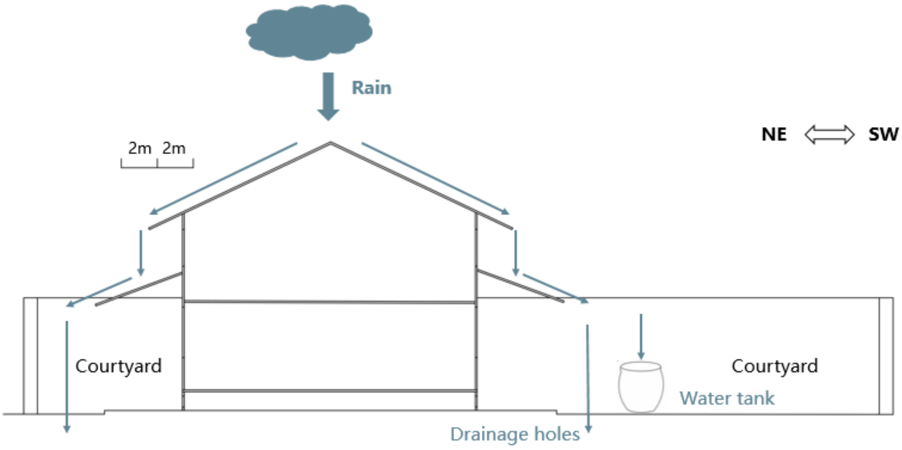


Figure 4-10. Drainage diagram.

Figure 4-11. The Water tank.

Figure 4-12. The drainage hole.

4.7.10. Land saving

Land resources are the most valuable resources and assets for human production and living ecology. The Ningbo area has numerous hills and rivers and little arable land, so local traditional courtyard houses were constructed with great care to conserve land. Land conservation has two main meanings: saving land and improving land utilisation. Traditional buildings cannot improve land utilisation by increasing the number of storeys such as modern buildings for technical reasons, but people have a simple understanding of land conservation, the density of buildings is relatively high and people typically do not excessively pursue building area.

When the design of the traditional courtyard house focuses primarily on the courtyard space, with more emphasis on achieving harmony between the building and the courtyard space, the internal arrangement of the building is weakened. Yan's former residence is 12.39 m in length and 7.3 m in width, with three rooms on each floor; the front courtyard is 12.39m long and 6.65 m wide, with an area ratio between the building and the front courtyard close to 1. This points to the fact that when building traditional courtyard houses, people did not aim for a large building area and had a sense of land conservation.

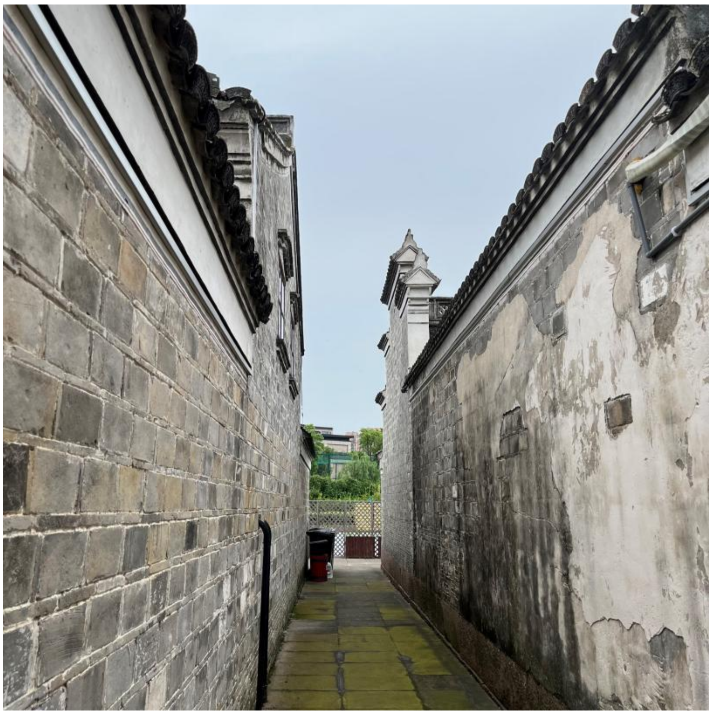


Figure 4-13. The street inside Yan's courtyard complex.

5. Field Analysis

The field monitor findings of temperature and humidity in summer and winter, as well as the results of simulations of the effects of various climate adaptation strategies on thermal, lighting, and wind environments in Ecotect climate data simulation software, is presented in this chapter.

5.1. Field monitor result

Winter monitoring data was obtained between January 6 and January 10, 2022. The summer monitoring data was collected between July 14 and July 18, 2022. This section displays the monitoring results of the temperature and relative humidity and analyses the thermal comfort percentage, temperature, and relative humidity fluctuation patterns, along with the temperature difference between indoor and outdoor.

5.1.1. Temperature

As displayed in Table 5-1, during the monitoring period in July, the indoor temperature fluctuations in the three buildings ranged from 35.89°C to 29.68°C, the temperature fluctuations in the three courtyards ranged from 42.79°C to 31.26°C and the outdoor temperature fluctuations ranged from 40.0°C to 26.0°C. The indoor temperature fluctuation values were consistently within the temperature fluctuation ranges of the outdoor and courtyard values. With the exception of C1, where the temperature fluctuations were within the outdoor temperature fluctuation range, the other two courtyards had maximum temperatures that were higher than the upper limit of the indoor temperature fluctuation range.

Throughout the monitoring period in January, the temperature fluctuations in the three buildings ranged from 15.64°C to 6.59°C indoors, 14.67°C to 3.18°C in the courtyard, and 3°C to 11°C outdoors. In contrast to the monitoring results from July, the upper range of fluctuations in I1 and I3 exceeded that of C1 and C3, and the upper range of indoor temperature fluctuations in all three buildings was more than those of the outdoor ones. The range of temperature fluctuations in C2 and C3 was greater in comparison to that of the outdoor ones.

The monitoring results for July and January together indicate that the temperature fluctuates to a lesser extent indoors than in the courtyard versus outdoors, with a smoother temperature indoors.

	Parameter	**I1**	**I2**	**I3**	**C1**	**C2**	**C3**	**Outdoor**
July	Max，℃	34.17	35.89	35.2	39.03	41.32	42.79	40
	Min，℃	30.69	29.68	30.26	28.25	28.8	28.93	26
January	Max，℃	11.52	11.74	15.64	11.07	14.67	14.64	11
	Min，℃	6.59	8.33	8.6	6.07	3.18	3.71	3

Table 5-1. Fluctuation range of the temperature of the building.

5.1.2. Relative humidity

As shown in Table 5-2, throughout the monitoring period in July, the relative humidity （RH） in the three buildings ranged from 44.97% to 73.2%, the relative humidity in the courtyard varied from 33.8% to 79.97%, and the relative humidity indoors fluctuated from 33% to 94%. The range of RH in the courtyard ranged from 48.38% to 97.39% and the range of RH indoors was in the range of 58% to 100%.

In July and January, there was a consistent trend between indoor and courtyard RH and outdoor RH fluctuations, that is, the indoor RH was always within the range of the courtyard and outdoor RH fluctuations. In contrast to January, when the minimum range of C2 and C3 was less than the minimum range of outdoor humidity, the RH in the courtyard was within the range of the outdoor RH fluctuations in July. The indoor and courtyard humidity levels are always higher in winter than in summer.

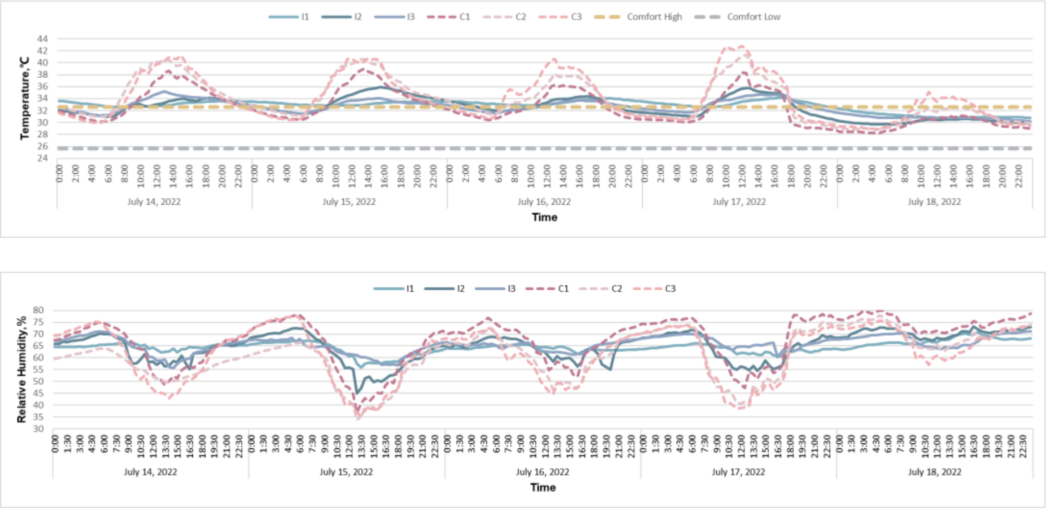
	Parameter	I1	I2	I3	C1	C2	C3	Outdoor
July	Max，%	70.98	73.2	71.21	79.97	77.98	77.65	33
	Min，%	55.92	44.97	55.69	36.79	33.8	35.19	94
January	Max，%	76.74	74.26	73.79	83.75	97.39	92.72	58
	Min，%	60.24	58.01	50.55	58.07	48.38	50.19	100

Table 5-2. Fluctuation range of the relative humidity of the building.

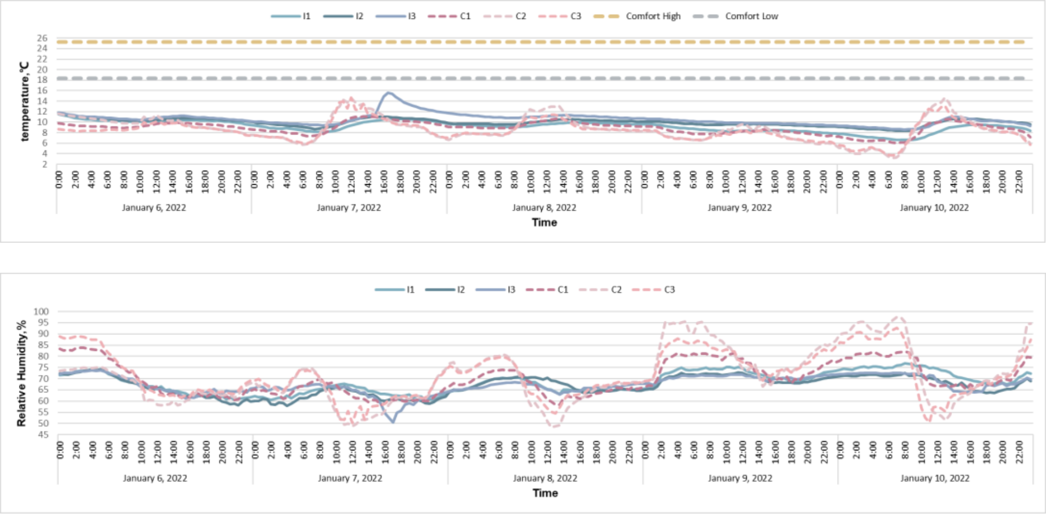
5.1.3. Thermal comfort percentage

For assessing the thermal comfort of the three naturally ventilated traditional buildings the adaptive comfort model was employed. The percentage of time that the three traditional buildings achieved thermal comfort was computed based on the comfort temperature range of the general adaptive comfort equation in China.

The winter results, in accordance with Figure 5-1, show that none of the three buildings can satisfy the comfort requirements. In summer the comfort requirements are largely met at night and only rarely during the day, however, all three buildings achieved the comfort range throughout the day on 18 July. The percentages of time comfort achieved in summer for I2 and I3 were 53.75% and 52.5% respectively, with comfort requirements being met more than half the time. On the other hand, I1 performed less well in summer with a comfort percentage of only 24.58%.



a. temperature and relevant humidity in summer.



b. temperature and relevant humidity in winter.

Figure 5-1. Seasonal temperature and relevant humidity.

5.1.4. Temperature and relative humidity fluctuation patterns

From the simulation results of the summer temperatures (Figure 5-1), it can be seen that the temperature fluctuation trends in the three courtyards were basically the same. The courtyard experienced its lowest temperature of the day between 5 and 6 am, followed by a rise in temperature that peaked between 3 and 4 pm, before beginning to fall. The indoor temperature trend was basically similar to that of the courtyard, with I2 and I3 having essentially the same indoor temperature fluctuation trend, but I1 took longer to reach its maximum and minimum values for the day compared to the former two. In terms of temperature fluctuations, C3 had the largest fluctuations and C1 had the smallest, while I2 had the largest fluctuations and I1 had the smallest.

The outcomes of the winter temperature simulations reveal that the temperature fluctuations in the three courtyards followed the same trend, with the minimum value in the courtyard being between 5 and 6 a.m., followed by rising to a maximum value around 1-2 p.m., and then falling. C1 displayed the smallest fluctuations, while C2 showed slightly greater fluctuations in contrast to C3. The indoor temperature fluctuation trend was similar to the results for the courtyard and the indoor temperature trend was comparable for all three buildings. Overall, C1 experiences the least amount of temperature variation in both seasons.

According to the results of the simulation of the relative humidity in the courtyard in the summer months, the trend of fluctuations in relative humidity in the three courtyards follows the same pattern, peaking between 6-7 pm during the day, with humidity beginning to fall, reaching a minimum at 12-1 pm and then beginning to rise. The indoor RH trend was similar to that of the courtyard. The relative humidity fluctuations in the three courtyards were close to one another, but the relative humidity in C1 was always slightly higher, while in C2 and C3 it was more or less the same.

The trend of fluctuations between the courtyard and the room, according to the winter RH simulation results, was largely the same as in the summer, with the highest fluctuations occurring in C2 and the lowest in C1. In contrast to C1, which had the opposite pattern, C2 had the lowest RH for a small part of the day and the highest RH for most of the night. The trend and degree of fluctuation in RH were roughly the same for all three rooms, with I1 having a higher RH for longer periods of time.

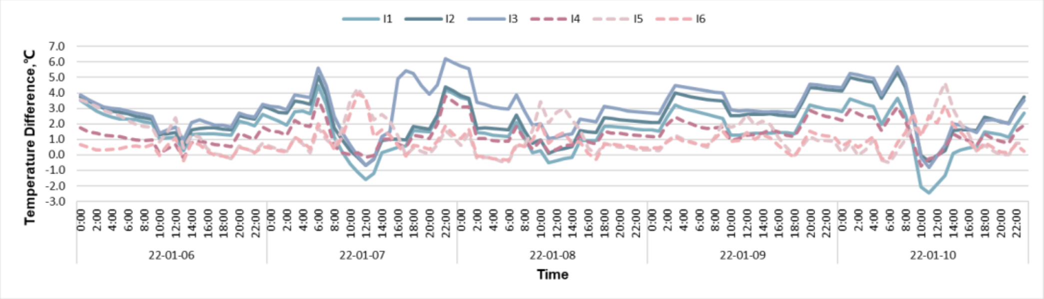
5.1.5. Temperature difference

The temperature difference between the indoor temperature minus the outdoor temperature and the temperature difference between the courtyard temperature minus the outdoor temperature is illustrated in figure 5-2. In accordance with the difference between indoor and outdoor temperatures in summer, all three buildings had lower indoor than outdoor temperatures during the day, and higher indoor than outdoor temperatures at night. Based on the indoor-outdoor temperature difference in winter, only a small part of the daytime (10:00-13:00) was cooler in comparison to the outdoor temperature in all three buildings, and most of the time the temperature was higher than the outdoor temperature. In summer, I1 was the coldest during the day and the hottest at night, whereas I2 and I3 were always close to one another. In winter, I1 was the coldest and I3 was the warmest throughout the day. I1 was, thus, consistently the coldest during the day.

According to the difference between the courtyard and outdoor temperatures, in summer, the three courtyards were warmer than the outdoors at night, and during the day, C2 and C3 were warmer than the outdoors. Conversely, in winter, the courtyards were generally warmer than the outdoors. In summer, the coldest courtyard throughout the day was Court C1, with C3 exhibiting hotter hours than C2 during the day, and the opposite at night.

When comparing the temperature differences between the courtyard and the outdoors and between the indoors and the outdoors, in winter the indoor temperature was higher than those of the courtyard for the majority of the day and lower than the courtyard for a small part of the day. In summer, the indoor temperature was much lower than the courtyard during the day and higher than the courtyard at night.

a. Temperature difference in summer.



b. Temperature difference in winter.

Figure 5-2. Seasonal temperature difference.

5.2. Thermal environment simulation results

5.2.1. Effect of different building layout forms on solar radiation

As can be observed from the solar radiation results of the three buildings (Figure 5-3) that the distribution of thermal radiation in the interior was relatively uneven, basically being higher near the doors as well as windows, with a decreasing trend from the doors and windows to the interior. The courtyard's solar radiation measurements revealed that outdoor solar radiation is also unevenly distributed, essentially the highest in the centre of the courtyard. There is a definite decreasing trend from the middle of the courtyard towards the walls and buildings, and a clear downward trend beneath the eaves. In both winter and summer, the courtyard is exposed to a lot more solar radiation than the inside.

Yan's public granary was modelled with both facing south-west (the current orientation) and facing south-east (i.e., the same orientation as Yan's ancestral hall and Yan's former residence). The findings demonstrate that altering the building's orientation has a slight but insignificant effect on solar radiation. Interestingly, when the public granary changed its facing to the south-east, the solar radiation inside was increased in both summer and winter. However, the front courtyard depicted an increase in solar radiation in winter and a decrease in summer, while the back courtyard showed the opposite, with a decrease in solar radiation in winter and a rise in summer.

The following simulations were carried out with all three buildings facing south-east in order to prevent the impact of varying orientations on the simulation findings because the simulations were created to examine the impact of various building layouts on solar radiation.

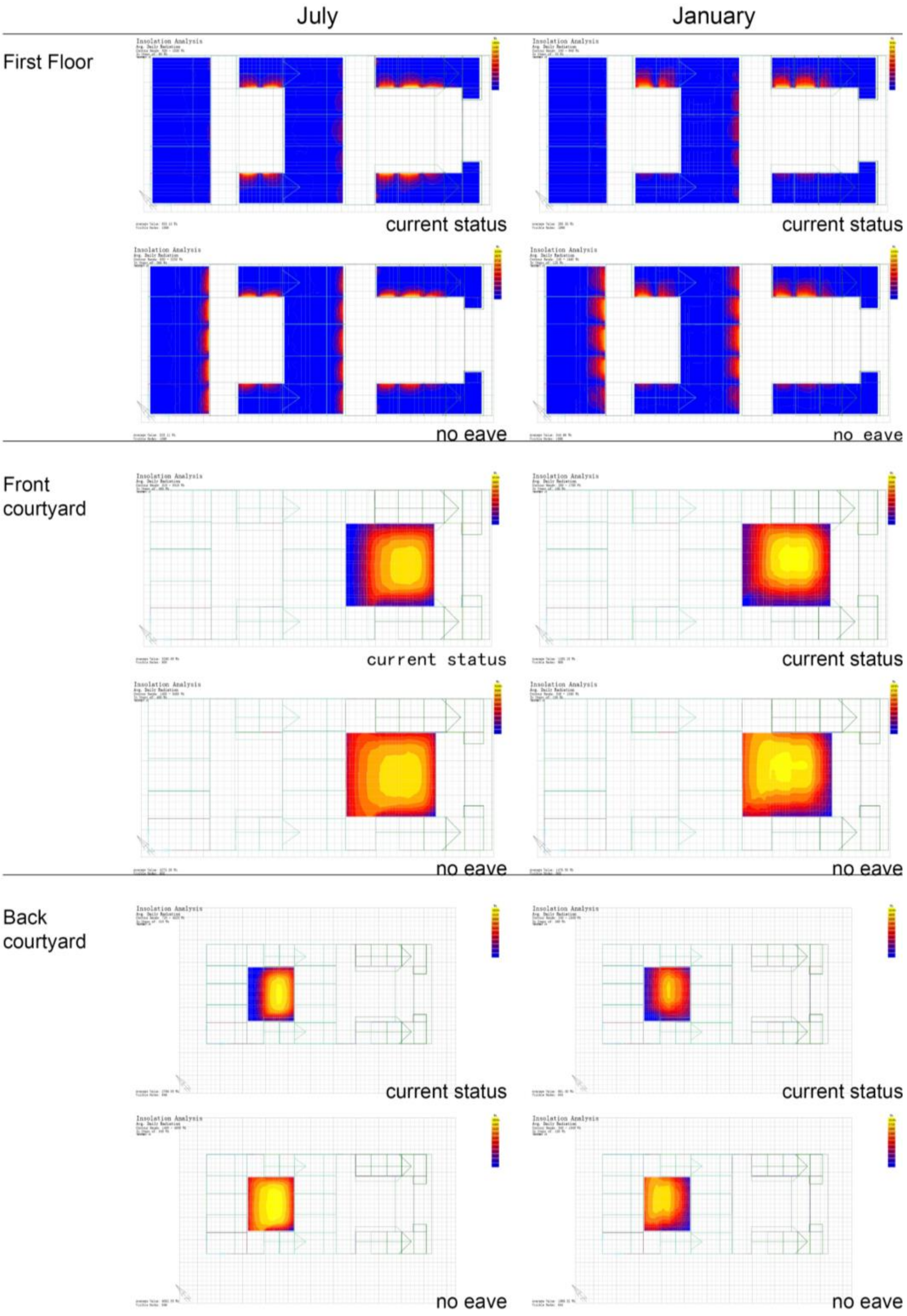
The summer and winter solar radiation results showed consistency, with interiors or courtyards that received higher solar radiation in summer tending to have higher solar radiation in winter as well. The summer and winter solar radiation results for the interior were ranked from smallest to largest according to the simulated results: public granary 2nd floor < former residence 2nd floor < public granary 1st floor < ancestral hall 1st floor < former residence 1st floor. The simulated summer, as well as the winter solar radiation results for the courtyard together, indicate that: the back courtyard of the public granary < back courtyard of the former residence < back courtyard of the ancestral hall < front courtyard of the ancestral hall < front courtyard of the former residence < front courtyard of the public granary.

In both winter and summer, the side houses on either side of the ancestral hall receive considerably higher solar radiation than the main house in the middle, while in winter the east chamber receives more heat than the west chamber. Nevertheless, in summer the west side house is closer to the east side house. In winter, the southeast side of the first and second floors of the public granary gets increasingly more solar radiation than the northwest side, while in summer the northwest side is slightly higher in comparison to the southeast. This is consistent with the winter results for the left and right-side houses of the ancestral hall. Similarly, to the results for the two buildings mentioned earlier, the first and second floors of the former residence likewise get more solar radiation from the southeast than from the northwest in winter, and more from the northwest than from the southeast on the first floor in summer, but the second floor received close solar radiation from both sides.

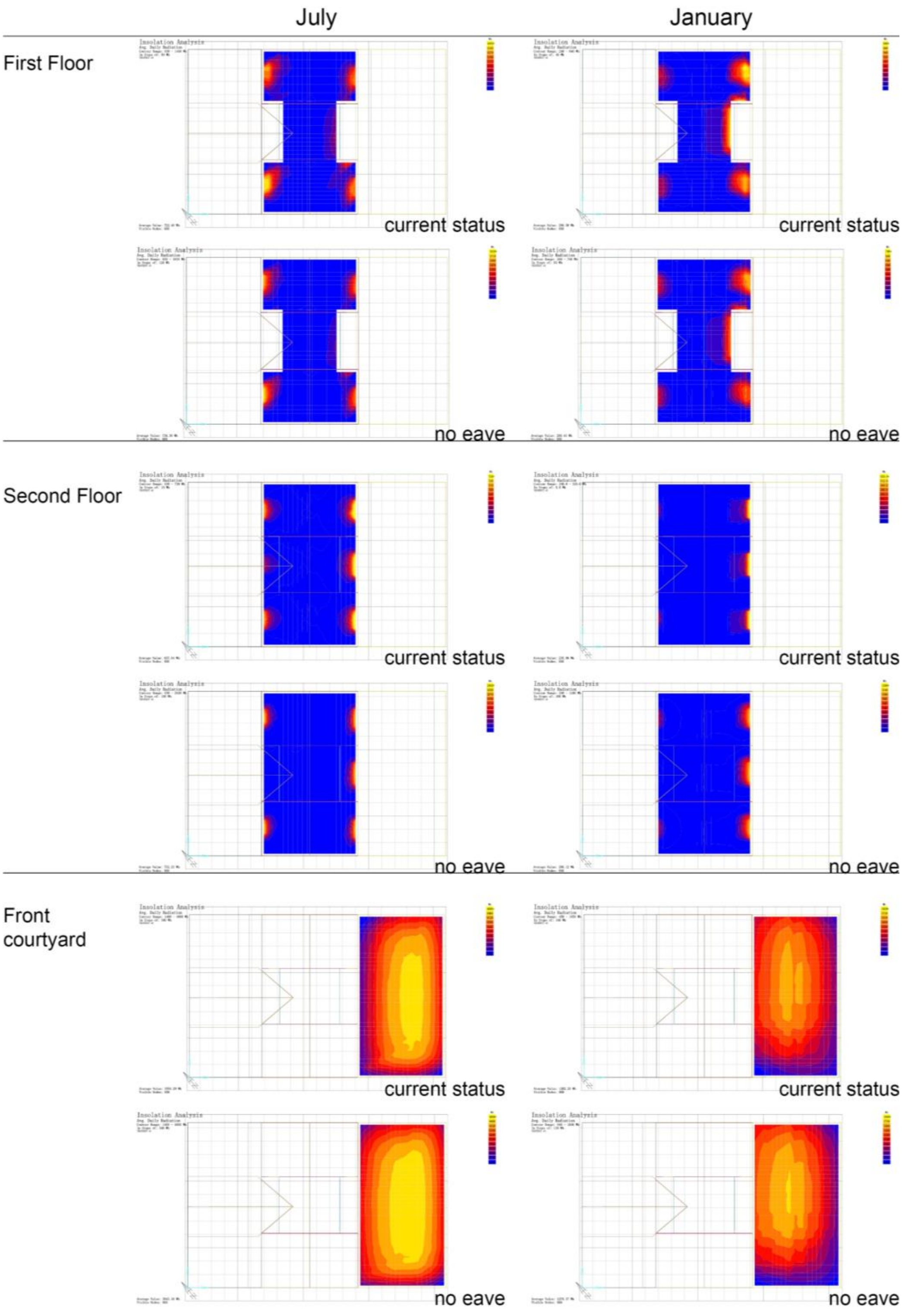
In light of the three buildings that have various forms of eaves, which may impact the simulation results, this study simulates the solar radiation without eaves shading, and the outcomes revealed that without the eaves shading solar radiation, the solar radiation of both the interior and the courtyard was noticeably increased. The ranking of solar radiation indoors yields slightly different results in the summer and winter, with the winter results being as follows: 2nd floor of the former residence < 2nd floor of the public granary < 1st floor of the former residence < 1st floor of the ancestral hall < 1st floor of the public granary; and the summer results as follows: 2nd floor of the former residence < 1st floor of the former residence < 2nd floor of the public granary < 1st floor of the ancestral hall < 1st floor of the public granary. The following are the summer and winter solar radiation results for the courtyard: back courtyard of the former residence < back courtyard of the public granary < front courtyard of the former residence < back courtyard of the ancestral hall < front courtyard of the ancestral hall < front courtyard of the public granary.

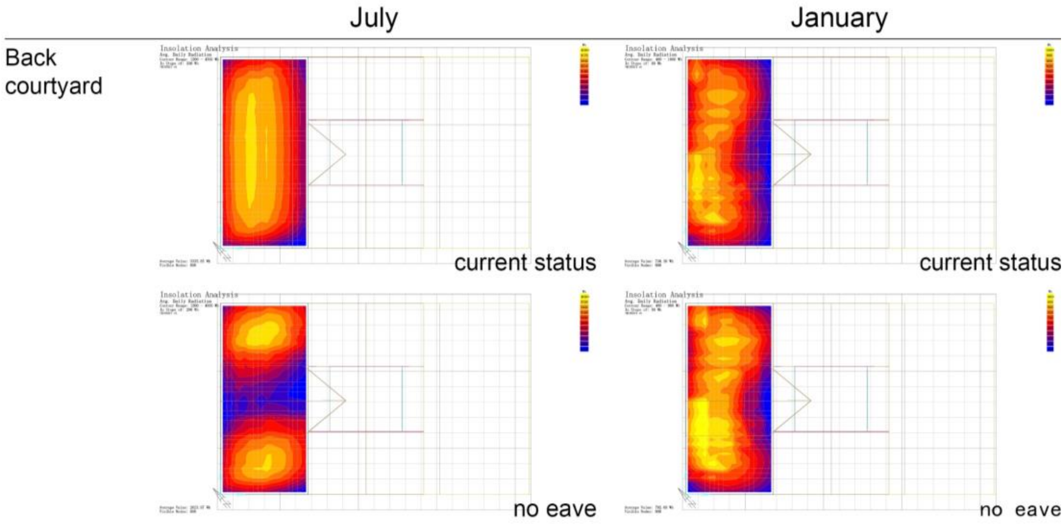
The east side home and the main house of the ancestral hall receive roughly the same solar radiation in the window position in summer and winter, and the west side house receives a little less. Without the eaves to shade the solar radiation, the solar radiation of both the main house and the side houses in the ancestral hall was substantially higher, but the increase in the main house was more obvious, and the increase in the solar radiation of the side houses was more significant in summer than in winter.

In winter, the solar radiation on the first and the second floors of the public granary is still higher on the southeast side than on the southwest side but in summer, the situation is still the opposite. The results for the former residence are consistent with earlier results, with the ground floor having higher solar radiation in the south-east in winter and higher solar radiation in the south-west in summer, and the second floor having higher solar radiation in the south-east in winter, with the south-east door being largely close to the south-west in summer.

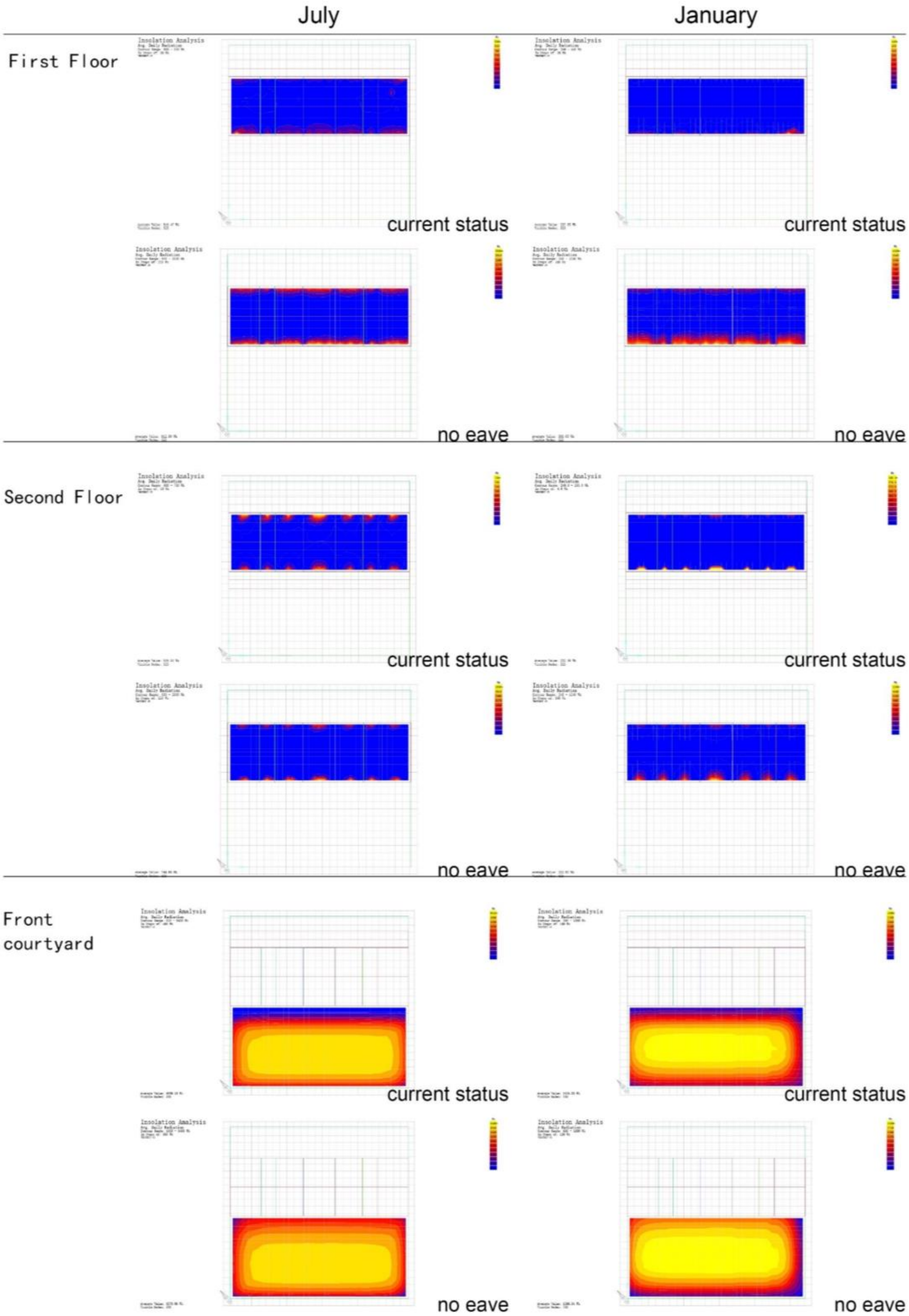


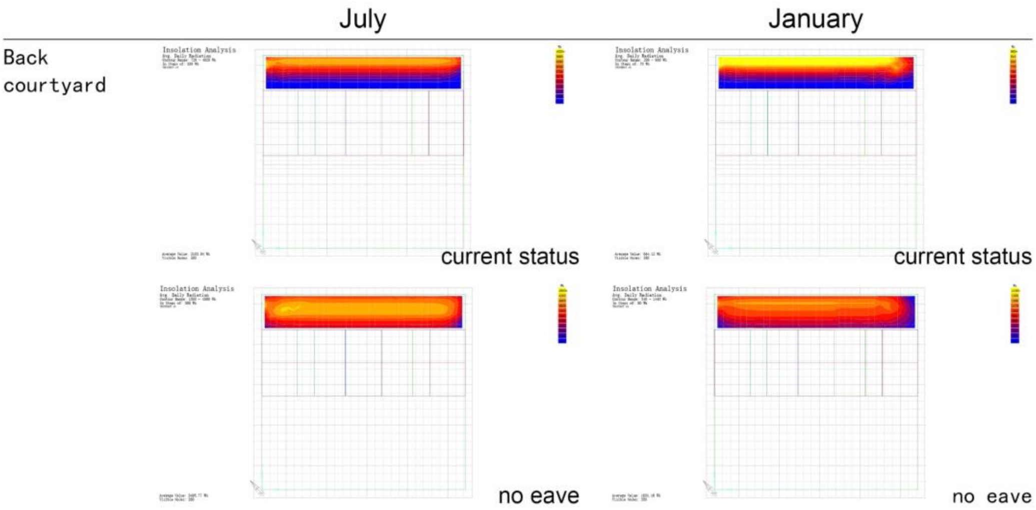
a. Solar radiation simulation results for Yan's ancestral hall.


July
January
First Floor
current status
current status
no eave
no eave
Second Floor
current status
current status
no eave
no eave
Front courtyard
current status
current status
no eave
no eave
Insolation Analysis

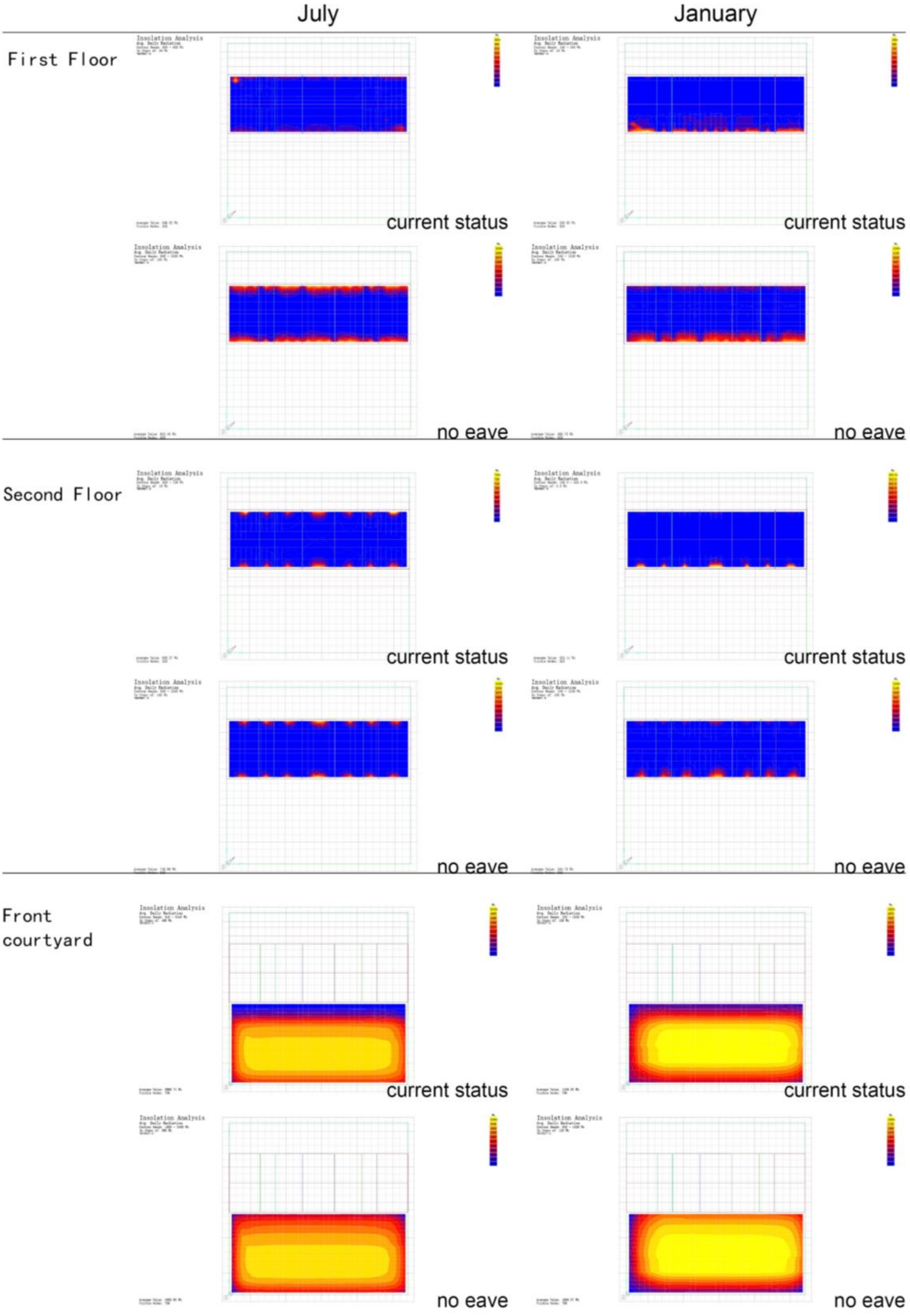


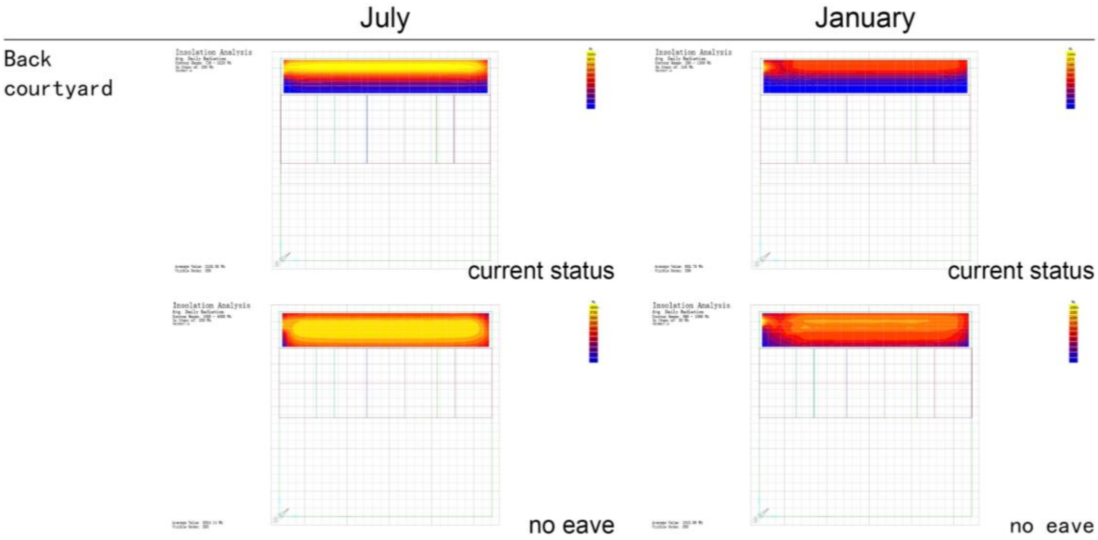
b. Solar radiation simulation results for Yan's former residence.


July
January
First Floor
current status
current status
no eave
no eave
Second Floor
current status
current status
no eave
no eave
Front courtyard
current status
current status
no eave
no eave
Insolation Analysis



c. Solar radiation simulation results for the Yan's public granary


July
January
First Floor
current status
current status
no eave
no eave
Second Floor
current status
current status
no eave
no eave
Front courtyard
current status
current status
no eave
no eave
Insolation Analysis

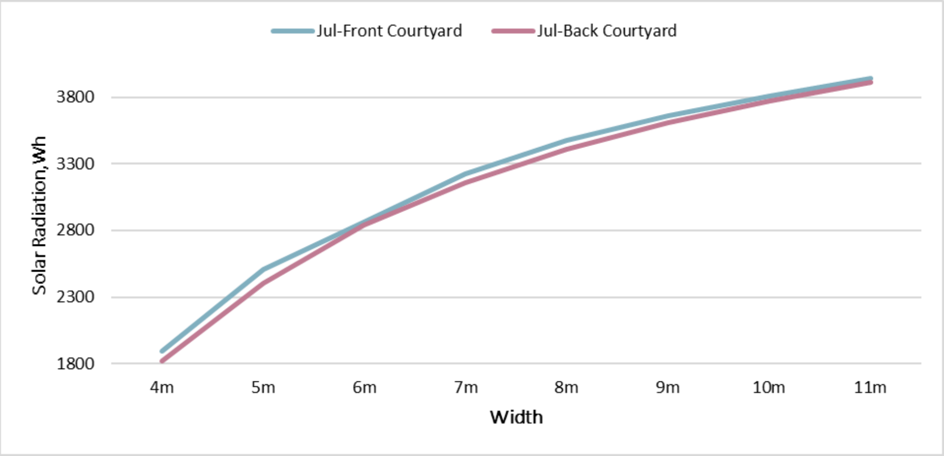


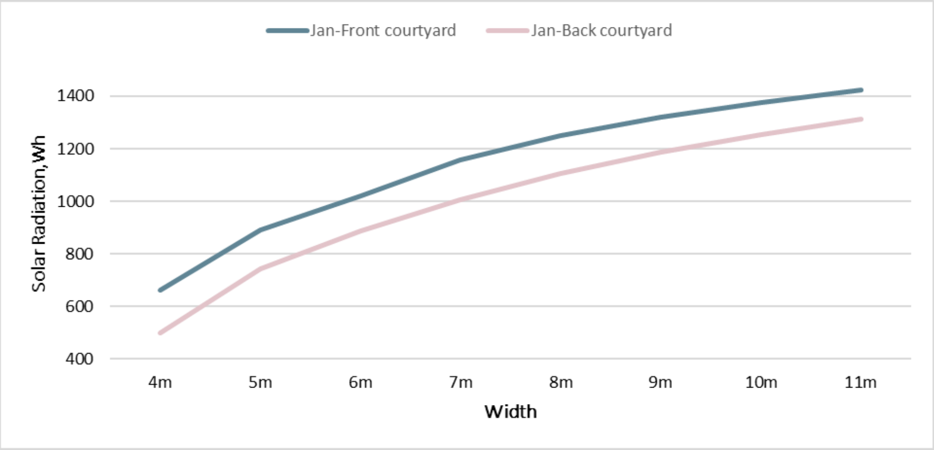
d. Solar radiation simulation results for Yan's public granary facing south-east.

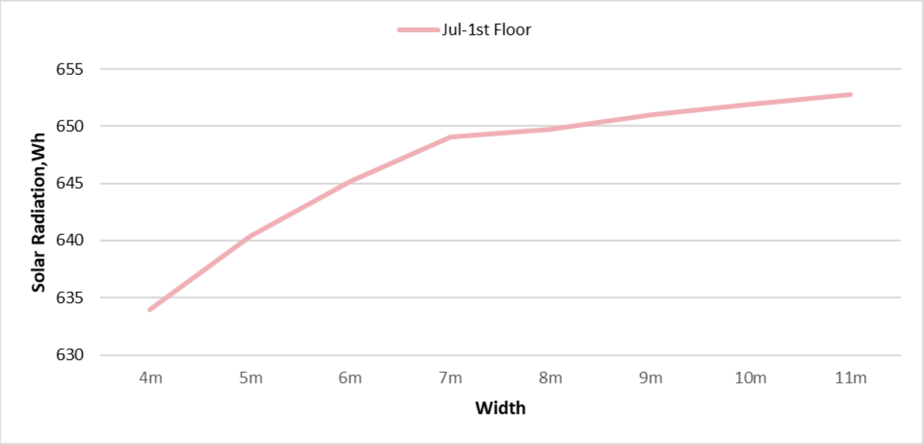
Figure 5-3. Solar radiation of Yan's ancestral hall, Yan's former residence, and Yan's public granary.

5.2.2. Effect of different courtyard widths on the solar radiation of buildings

The overall trend indicated that the courtyard's width increased the amount of solar radiation it received in both summer and winter, while the interior's trend is noticeably smaller than the courtyard's. According to the simulation results of the courtyard, the solar radiation obtained from the courtyard always increased as the width increased, although the tendency to increase gradually decreased. The solar radiation in the front courtyard was always higher than in the back courtyard. The simulation results of the 1st-floor interior pointed out that the solar radiation in the interior increased as the width of the courtyard increased, but when the width of the courtyard exceeded 7, the trend of rise became less obvious.


Jul-Front Courtyard
Jul-Back Courtyard
Solar Radiation,Wh
3800
3300
2800
2300
1800
4m
5m
6m
7m
8m
9m
10m
11m
Width


Jan-Front courtyard
Jan-Back courtyard
Solar Radiation,Wh
1400
1200
1000
800
600
400
4m
5m
6m
7m
8m
9m
10m
11m
Width


Jul-1st Floor
Solar Radiation,Wh
655
650
645
640
635
630
4m
5m
6m
7m
8m
9m
10m
11m
Width

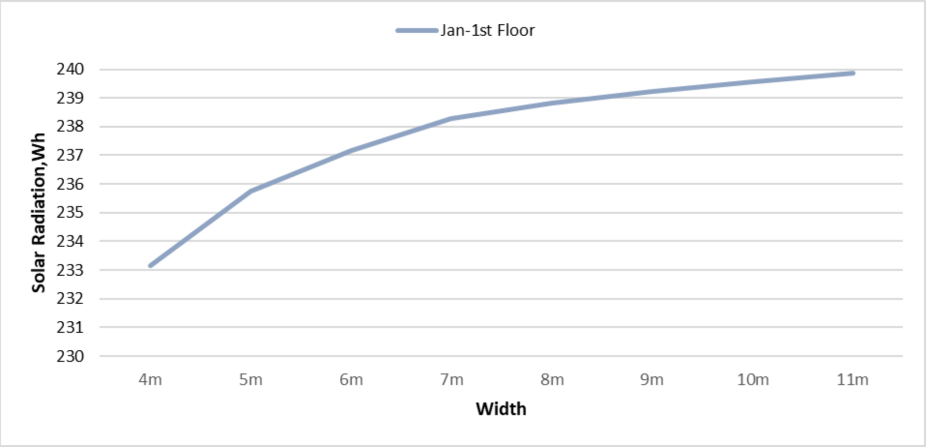
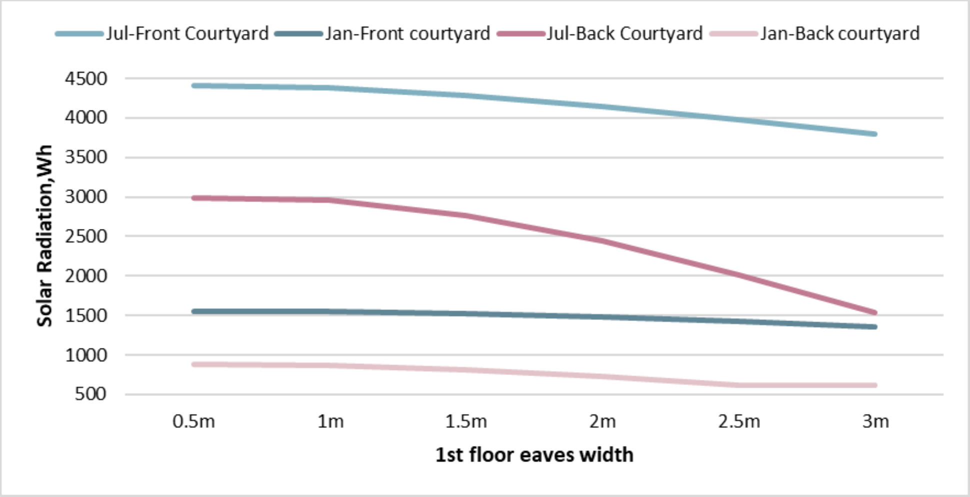


Figure 5-4. Solar radiation of front courtyard, back courtyard, and 1st floor at different courtyard widths.

5.2.3. Effect of different eaves widths on the solar radiation of buildings

The overall results showed that when the width of the first and second-floor eaves increased from 0m to 4m, the solar radiation received by both the interior and the courtyard decreased. The increase in eaves width, nevertheless, had a significantly smaller impact on the interior than on the courtyard. For both courtyards, the increase in eaves width had a greater influence on the rear courtyard. According to the simulation results for the courtyard, the tendency of reducing the solar radiation received by the courtyard increased with the increase of the width of the eaves. According to the simulation results for the first and second-floor interiors, the solar radiation acquired by the interior decreases as the width of the eaves increases, and the trend of decreasing solar radiation obtained by the interior of the first floor was less evident when the width of the eaves on the first floor was greater than 2m. Moreover, when the width of the eaves on the second floor was greater than 1m, the trend of decreasing solar radiation obtained by the interior of the first floor was less apparent.



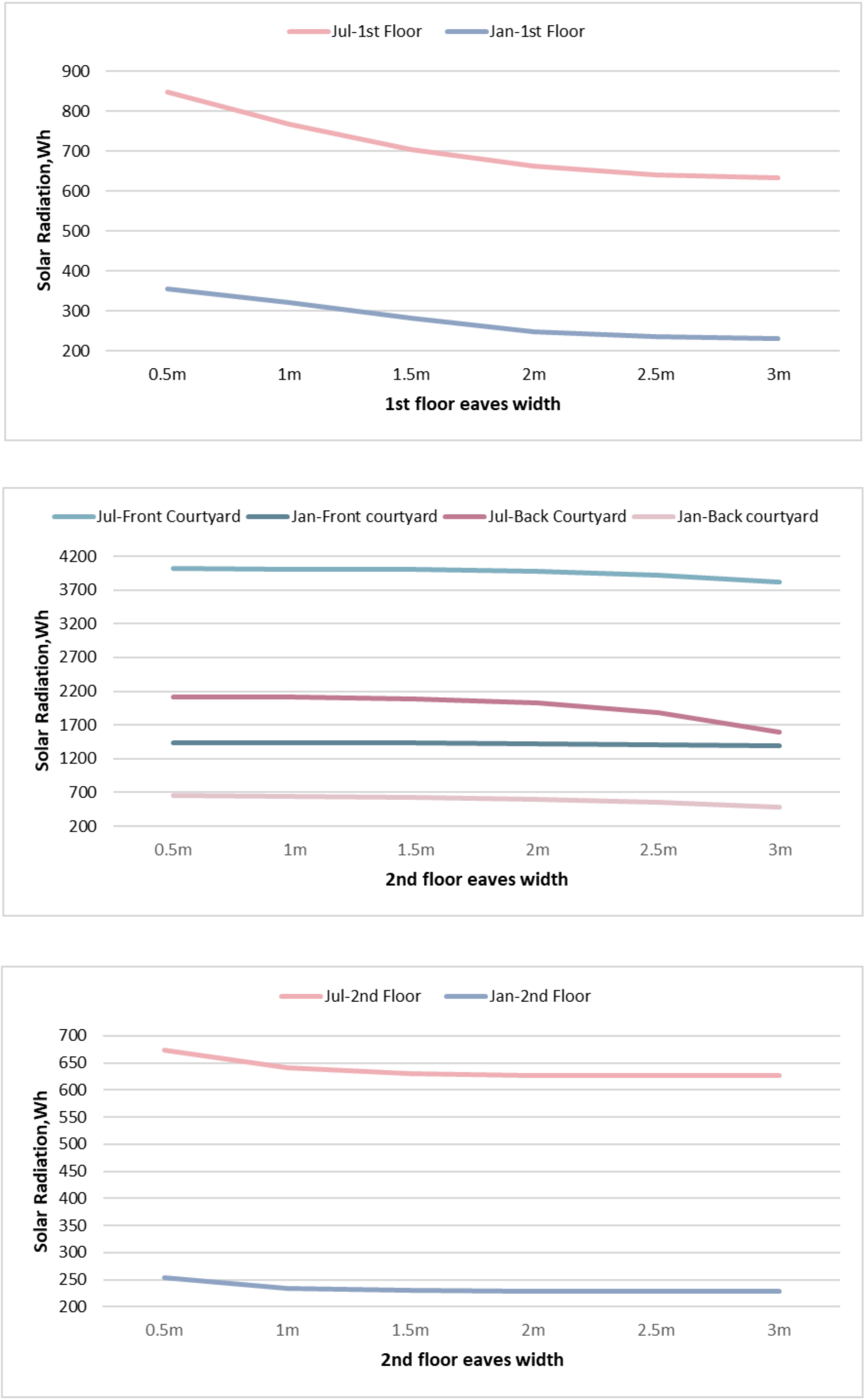


Figure 5-5. Solar radiation of front courtyard, back courtyard, 1st floor, and 2nd floor at different eaves widths.

5.3. Lighting environment simulation results

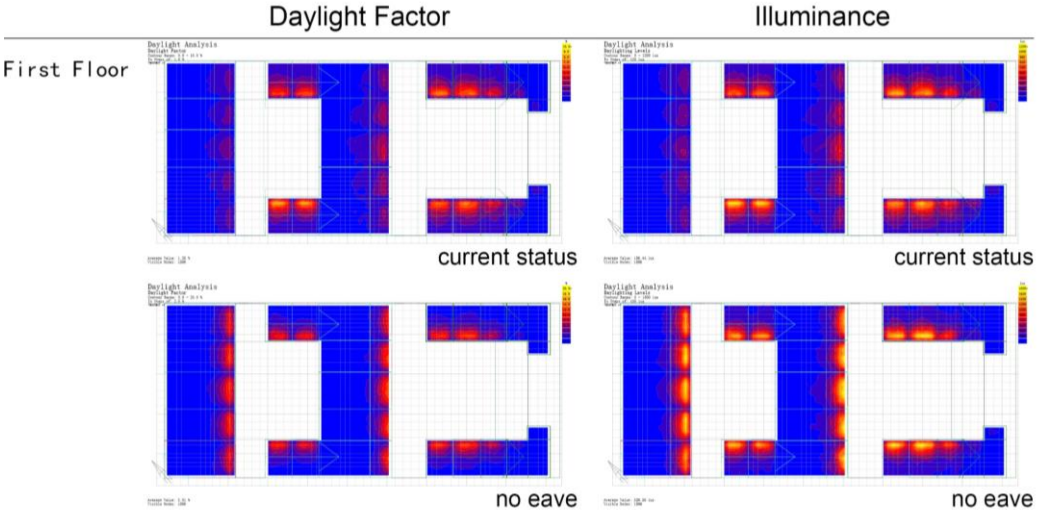
5.3.1. Effect of different building layout forms on daylighting factor and illuminance of buildings

The general pattern revealed some consistency in the daylighting factor and illuminance, as well as a non-uniform distribution of solar illuminance and daylighting factors, with greater values near the doors and windows and decreasing towards the interior. The results of the simulations also show that changing the orientation of the building had no effect on the interior lighting of the building, along with the daylighting factor and illuminance of Yan's public granary with the same orientation as Yan's former residence and Yan's ancestral hall.

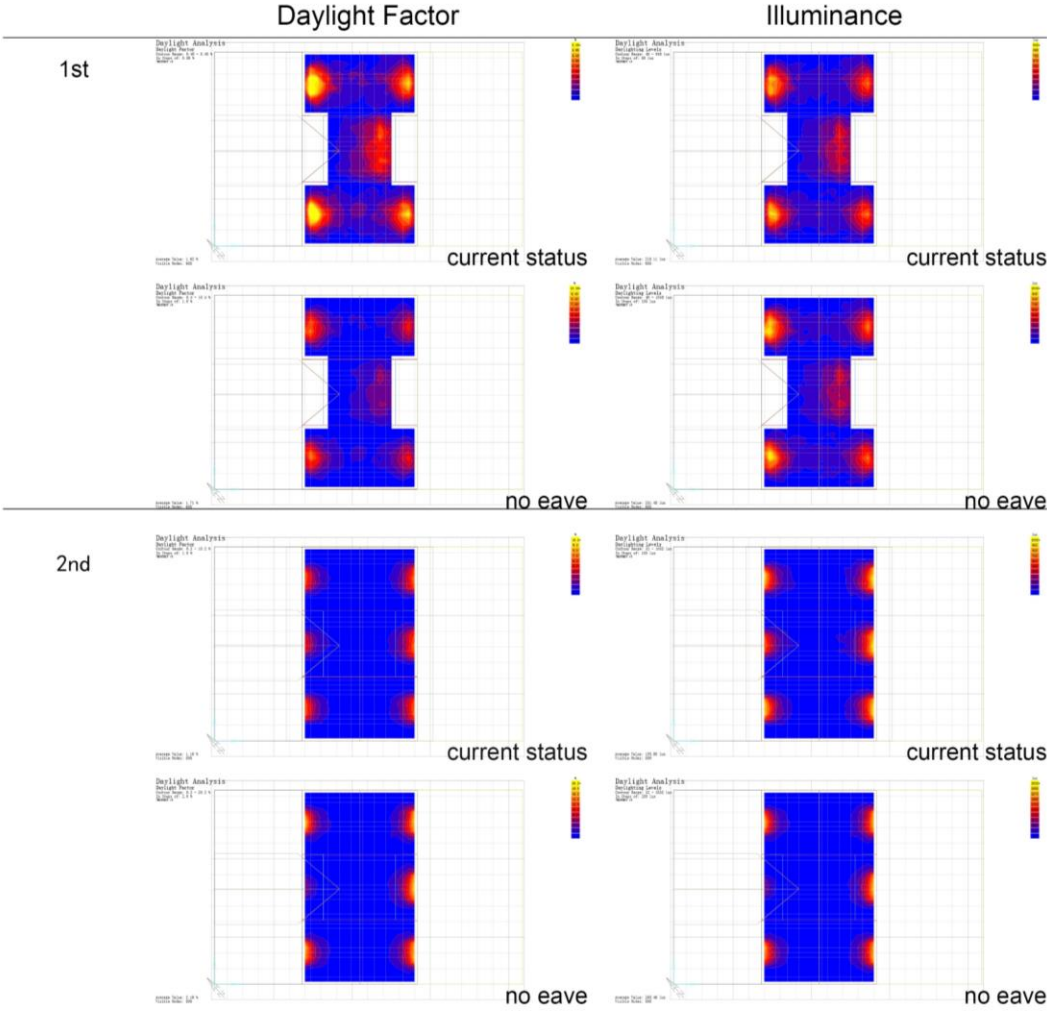
The simulations results were ranked from smallest to largest in terms of daylighting factor and illuminance: the 2nd floor of the public granary < the 2nd floor of the former residence < 1st floor of the Ancestral Hall < the 1st floor of the former residence < the 1st floor of the public granary.

The main room of the ancestral hall received less illumination than the two side rooms, and the illumination of the main room by the front door received more than that of the main room inside. The illumination on the southeast side of the ground floor of the former residence was lower than that on the northwest side, and the first floor's two sides were close together. The illuminance on both sides of the granary was similar.

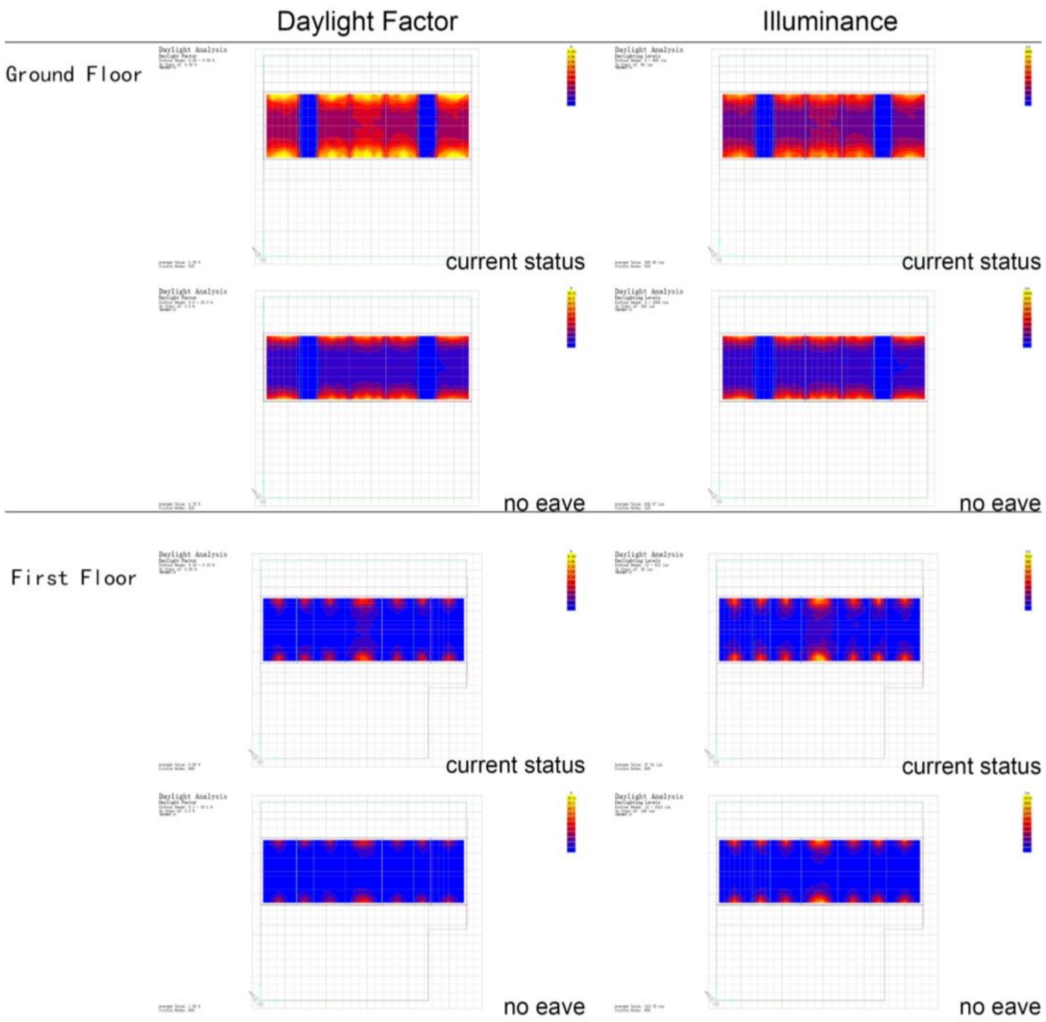
In addition, for the purpose of avoiding the effect of eaves on the light blockage, the situation without eaves was simulated. The results showed that the indoor lighting coefficient and illuminance of all buildings increased, in descending order of results: 2nd floor of the public granary < 1st floor of the former residence < 2nd floor of the former residence < 1st floor of the Ancestral Hall < 1st floor of the public granary. The illuminance of the main room of the ancestral hall improved significantly, and the ancestral hall and granary gained more or less the same illuminance in the window position. The illuminance of the southeast side of the former residence was still lower than that of the northwest side on the ground floor, and close on both sides of the first floor. Both sides of the granary had similar levels of illumination.



a. Daylighting factor and illuminance simulation results for Yan's ancestral hall.



b. Daylighting factor and illuminance simulation results for Yan's former residence.



c. Daylighting factor and illuminance simulation results for Yan's public granary.

Figure 5-6. Daylighting factor and illuminance of Yan's ancestral hall, Yan's former residence, and Yan's public granary.

5.3.2. Effect of different courtyard widths on daylighting factor and illuminance of buildings

The simulation results exhibited that increasing the width of the courtyard led to some improvement in the lighting of the first-floor interiors. However, this improvement trend decreased with the increase in the width.

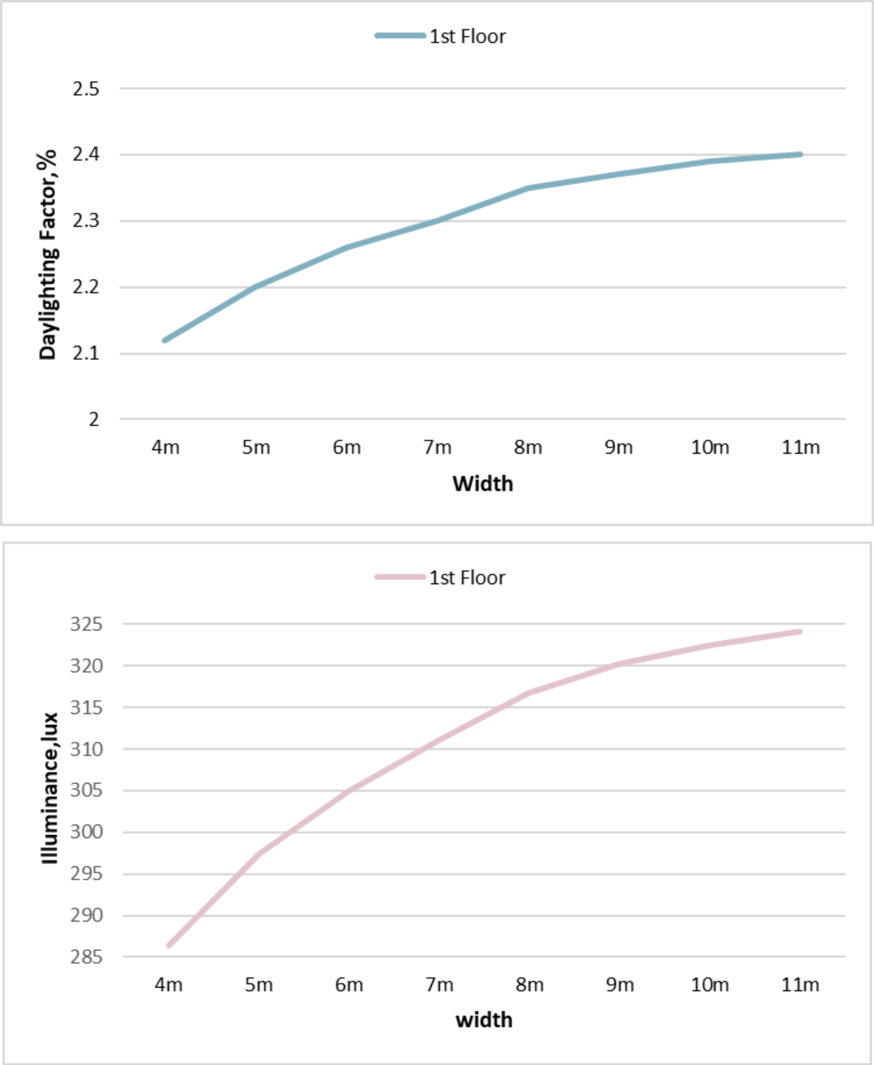
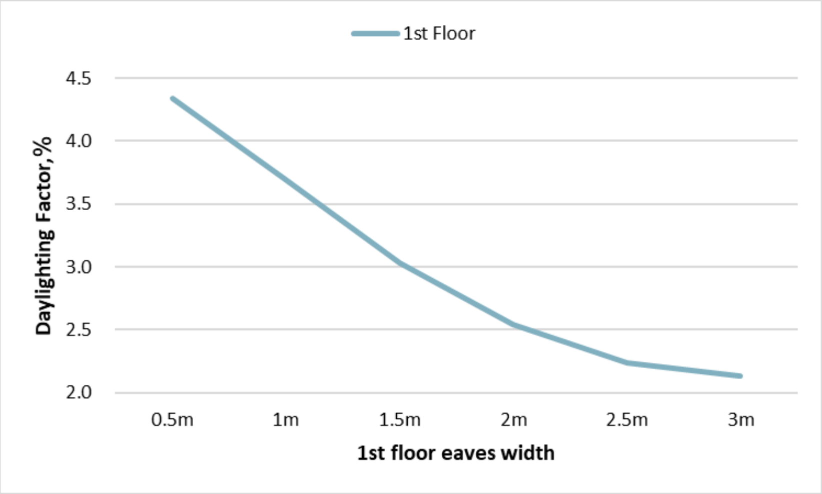
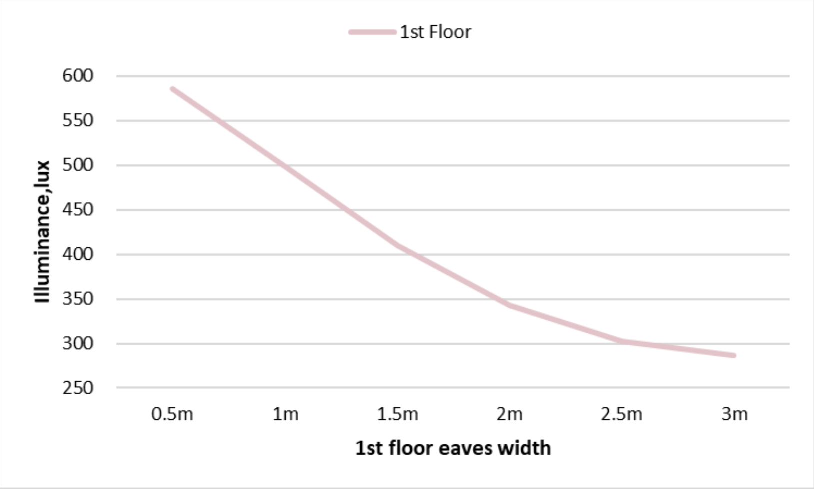


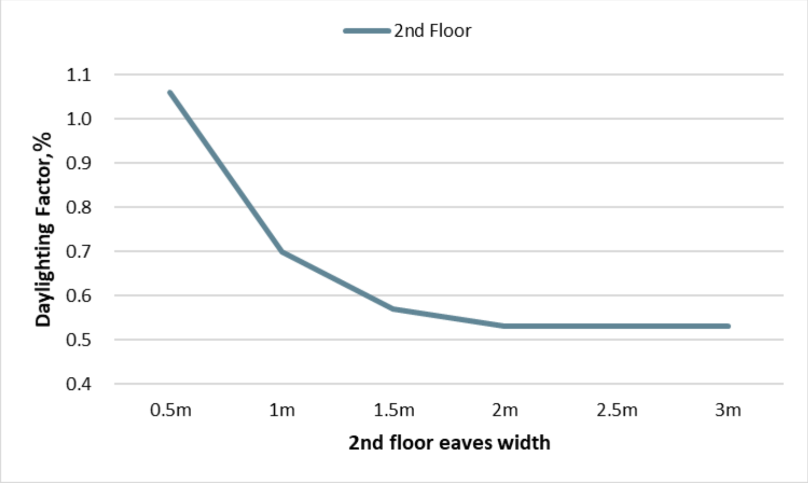
Figure 5-7. Daylighting factor and illuminance of 1st floor at different courtyard widths.

5.3.3. Effect of different eaves widths on daylighting factor and illuminance of buildings

Overall, as the width of the eaves increased on the first and second floors, the illuminance as well as the daylighting factor on the first and second floors each dropped. The daylighting factor and illuminance on the first floor decreased as the eaves width of the first floor increased from 0.5m to 3m, but the trend of decrease was diminishing. The daylighting factor and illuminance on the second floor decreased from 0.5m to 2m with the eave's width of the second floor, however, when the width of the eaves exceeded 2m, the decrease in daylighting factor and illuminance was no longer significant.


1st Floor
Daylighting Factor, %
4.5
4.0
3.5
3.0
2.5
2.0
0.5m
1m
1.5m
2m
2.5m
3m
1st floor eaves width


1st Floor
Illuminance,lux
600
550
500
450
400
350
300
250
0.5m
1m
1.5m
2m
2.5m
3m
1st floor eaves width


2nd Floor
Daylighting Factor, %
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.5m
1m
1.5m
2m
2.5m
3m
2nd floor eaves width

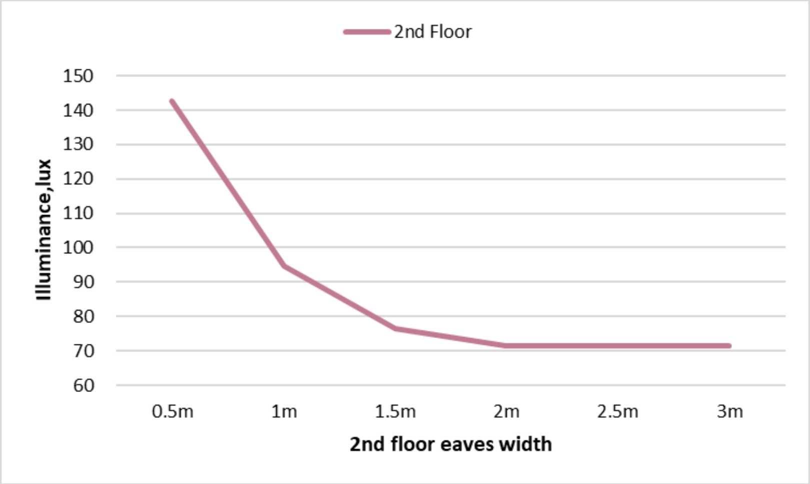


Figure 5-8. Daylighting factor and illuminance of 1st and 2nd floor at different eaves widths.

5.4. Wind environment simulation results

The average wind velocity at a height of 1.5m was chosen for the simulation to assess the wind environment at pedestrian height. The height of 0.5m was selected as the outdoor air waste accumulation study height. The average wind velocity at a height of 1.5m above the top of the first floor was chosen for evaluating the outdoor wind velocity entering the interior of the second floor, where 3.5m height was taken for Yan's public granary and 3m height for Yan's former residence.

5.4.1. Effect of different building layout forms on wind velocity

According to the simulation results, at a height of 1.5m, the wind velocity inside each of the three courtyards is basically below 1.2m/s, which is able to satisfy the human comfort requirements. At 0.5m height, the wind velocity rises with less significant air waste accumulation. The wind velocity in the courtyard at a height of 1.5m above the top of the first floor is always higher than that at 0.5m and 1.5m height. The possible reason for this is that the air circulation at lower heights is more easily obstructed by the courtyard walls, which leads to a drop in wind velocity. At the east and west corners of the courtyard's perimeter, wind velocities are consistently strong, peaking at 2.14m/s at 1.5m height and 1.8m/s at 0.5m height.

The simulation results for Yan's public granary show that the overall wind velocities in the front and back courtyard are comparatively similar in winter, while in summer front courtyard experiences significantly higher wind velocities than the back courtyard. This is because, in summer the prevailing wind direction is southeast, with the wind always blowing from the front courtyard to the back courtyard, whereas in winter the wind always blows in the other direction. In summer, the overall wind velocity in the back courtyard of Yan's former residence is lower than that in the front courtyard, while in winter the situation is reversed. In summer, the southeast wind, which blows from the front courtyard to the back courtyard has an effect on Yan's former residence. Obstructed by the roof above the back courtyard, the wind cannot pass smoothly, so the air circulation below the roof is not smooth and the wind velocity is below 0.5m/s. In winter, the wind blows from the back courtyard to the front courtyard owing to the north-westerly wind. The roof above the back courtyard has a relative influence on the air circulation in the back courtyard but prevents the air below the roof from flowing from the back courtyard to the front courtyard, hence, the wind velocity in the front courtyard is lower. The wind speed in the two courtyards of Yan's ancestral hall is generally close in winter and summer, and lower than that in Yan's public granary and Yan’s former residence. This can be because the building consistently blocks the wind from entering the courtyard.

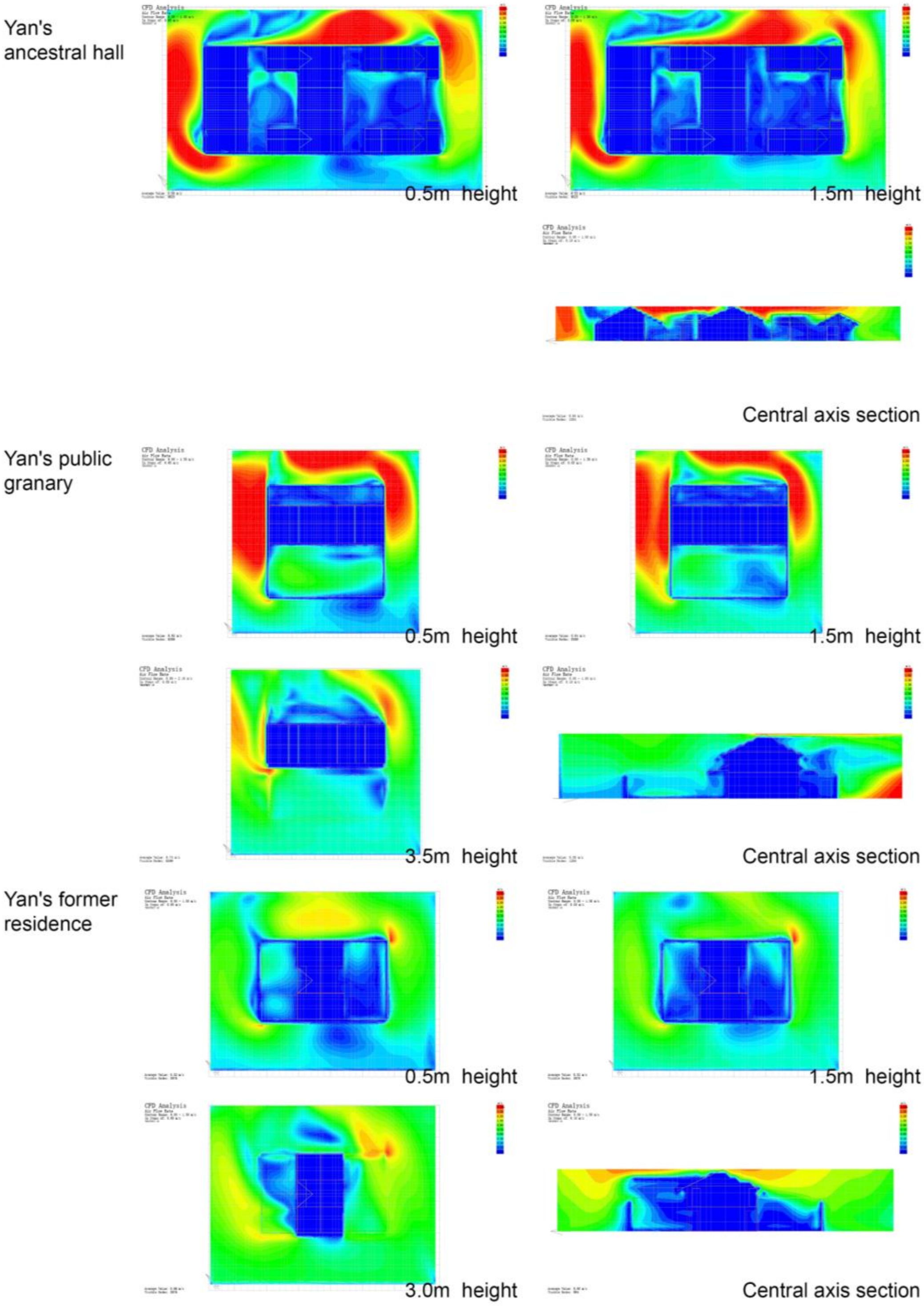


Figure 5-9. Wind velocity of Yan's ancestral hall, Yan's former residence, and Yan's public granary in summer.

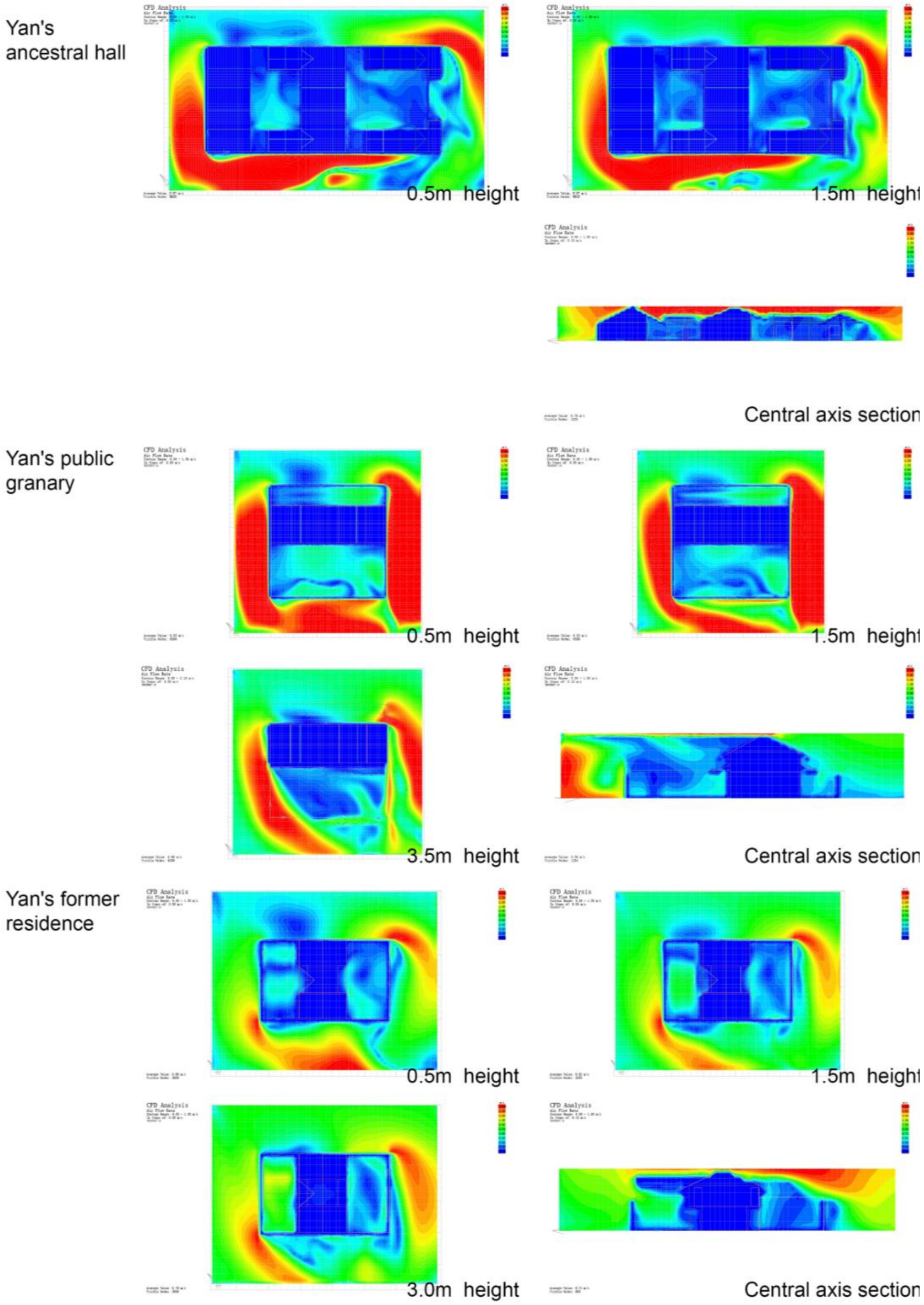


Figure 5-10. Wind velocity of Yan's ancestral hall, Yan's public granary, and Yan's former residence in winter.

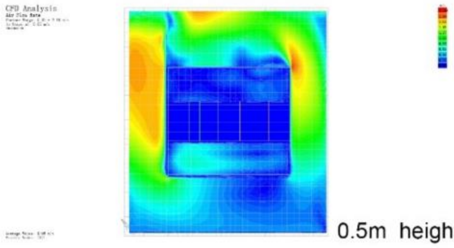
5.4.2. Effect of different courtyard widths on wind velocity

The winter simulation results reveal that the wind velocity in the front courtyard is essentially below 0.5 m/s at a yard width of 4 m, with poor air circulation and lower wind velocities in the front courtyard in comparison to the back courtyard, which has wind velocities below 0.5 m/s at 0.5 m and 1.5 m heights and up to 1.8 m/s at 3.5 m heights. The overall wind velocity in both the front as well as the back courtyard increases to a considerable level. At a courtyard width of 11m, the maximum wind velocity in the front courtyard reaches 0.65 m/s and 0.6 m/s, and 1.02 m/s in the back courtyard at 0.5m and 1.5m heights and 2.12 m/s in the front courtyard and 2.01 m/s in the back courtyard at 3.5m heights.

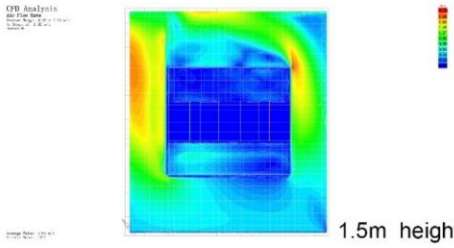
As the width of the courtyard increases, the tendency of wind vortexes forming beneath the eaves of the ground floor of the public granary becomes more pronounced while the tendency for cyclone airflow to form beneath the courtyard wall in the front courtyard increases, as does the wind velocity in the front courtyard. The increase in the width of the courtyard has an insignificant impact on the wind velocity in the space under the eaves of the back courtyard, but as the wind flows from the front to the back courtyard, the front courtyard's wind velocity rises ultimately increasing the airflow velocity in the back courtyard. As the width of the courtyard increases, there is likewise some increase in wind velocity under the eaves on the second floor, but it is less significant. The overall wind velocity in the back courtyard is always higher compared to the front courtyard. The findings of the summer simulations are similar to those of the winter, however, the wind velocity in the front courtyard is consistently higher than that in the back courtyard in summer. This might be related to the different directions of the prevailing wind in both summer and winter.

In conclusion, as the width of the courtyard increases, the overall wind velocity in the courtyard of the building rises dramatically, which improves air circulation.

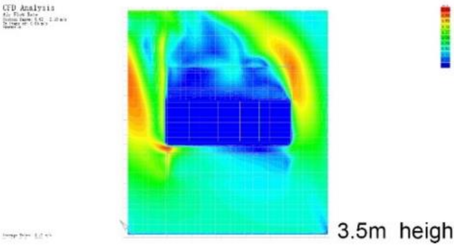
7m



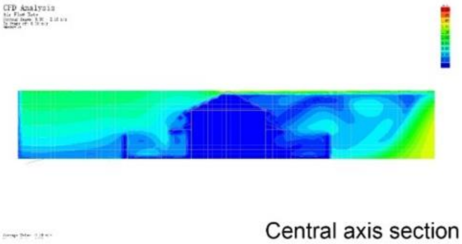
0.5m height



1.5m height

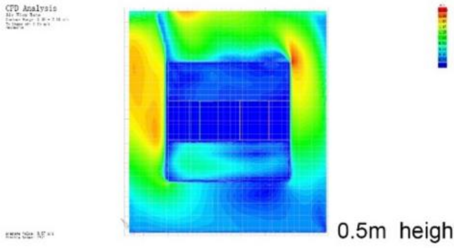


3.5m height

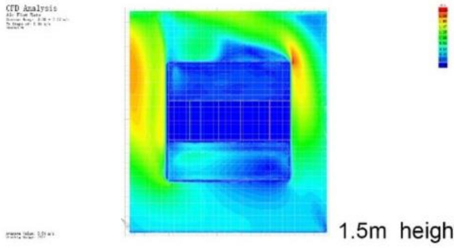


Central axis section

8m



0.5m height



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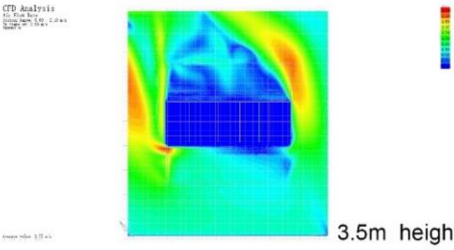

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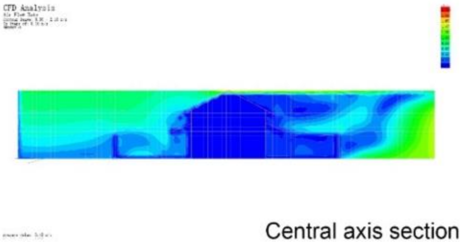
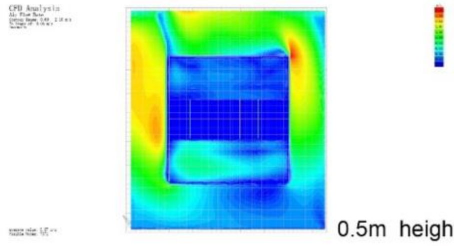


Central axis section

9m



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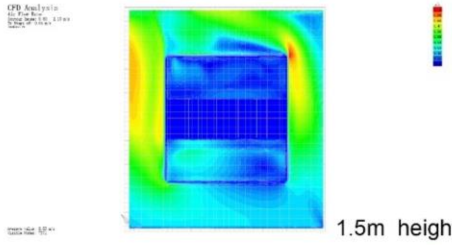

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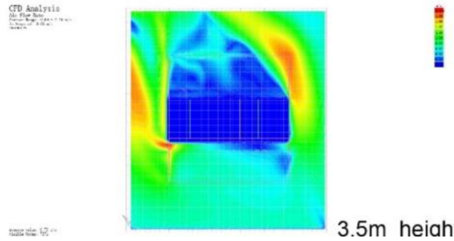

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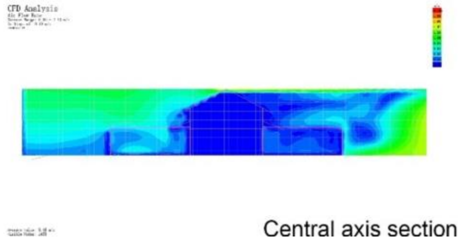
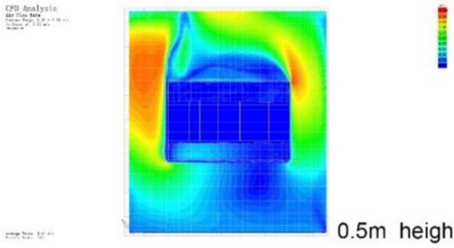


Central axis section

4m



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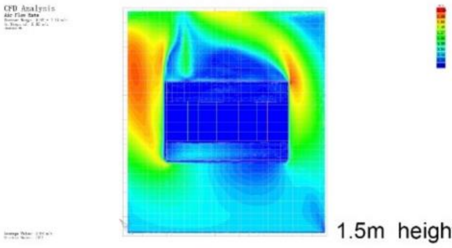

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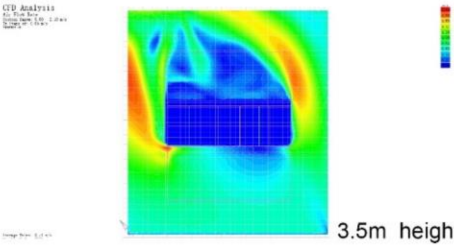

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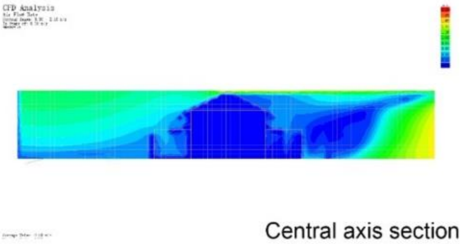
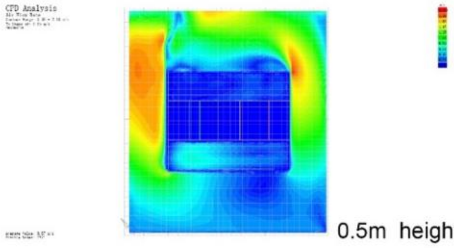


Central axis section

5m



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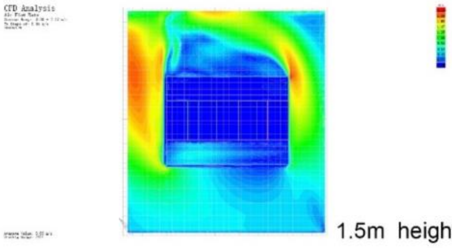

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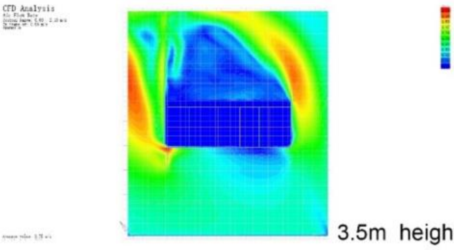

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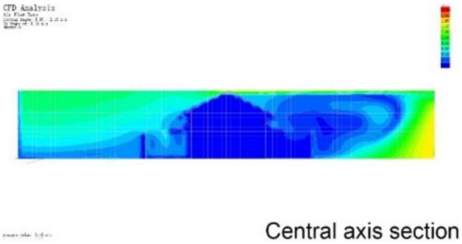
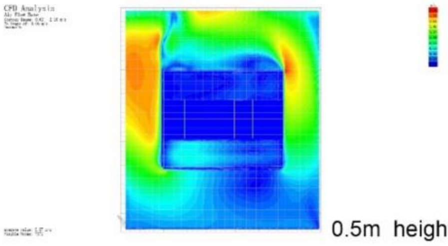


Central axis section

6m



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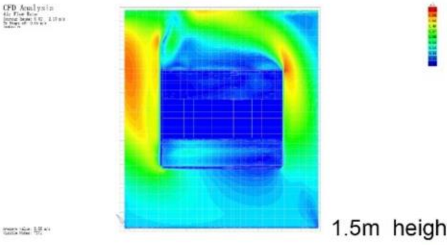

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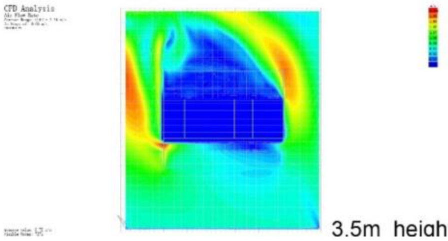

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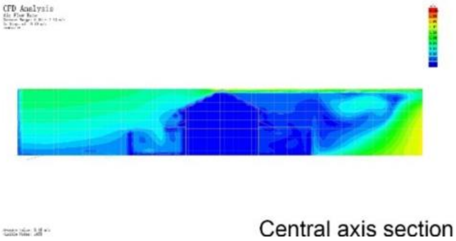


Central axis section

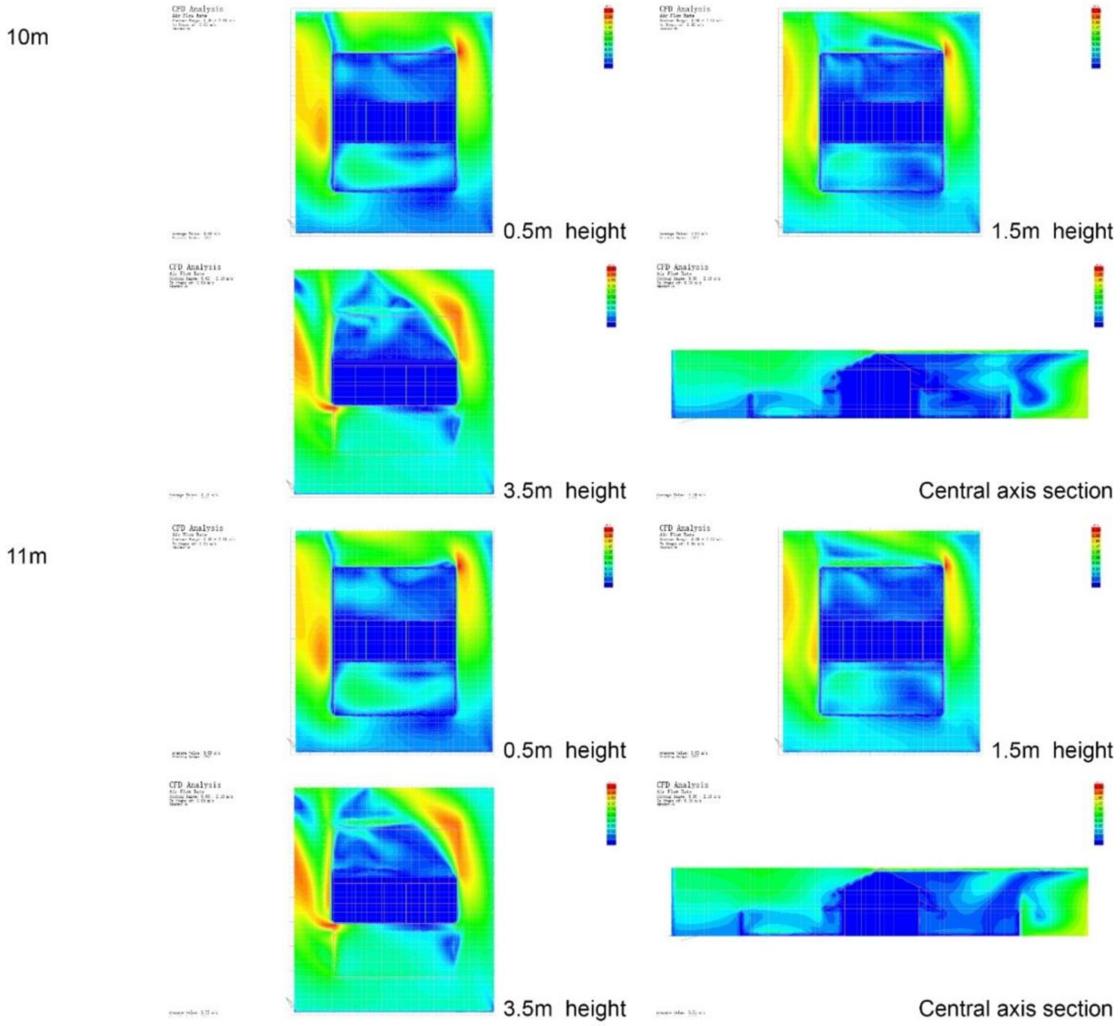
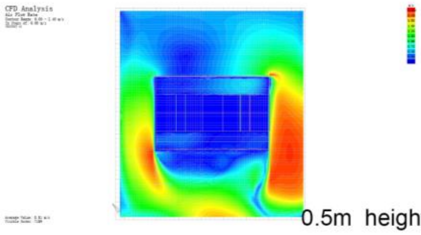


Figure 5-11. Wind velocity of Yan's public granary at different courtyard widths in summer.

4m



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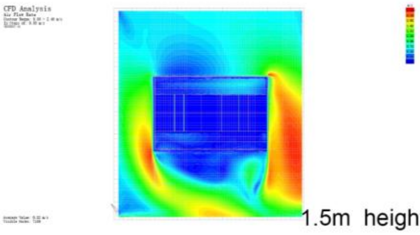

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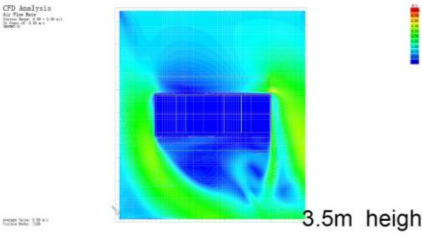
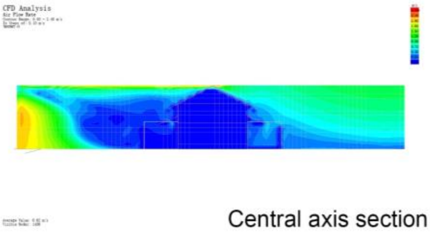
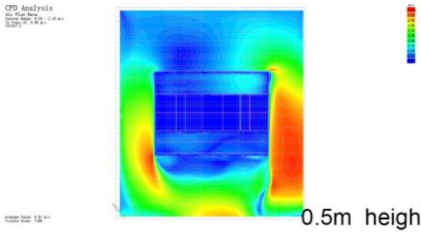


3.5m height



Central axis section

5m



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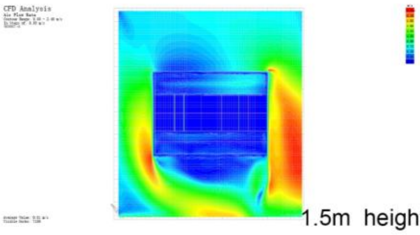

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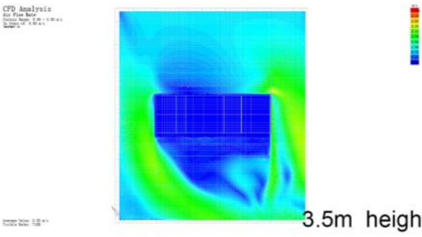

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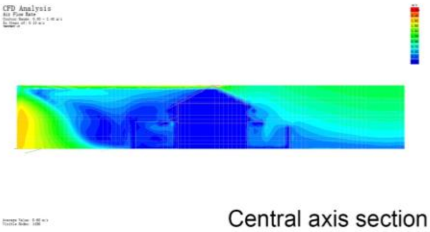
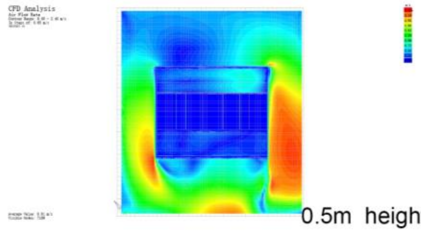


Central axis section

6m



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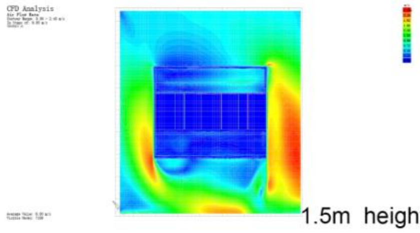

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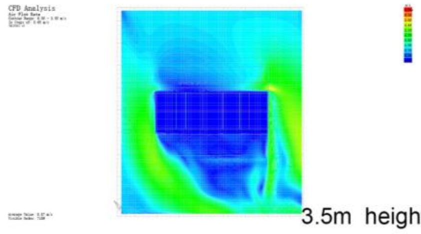

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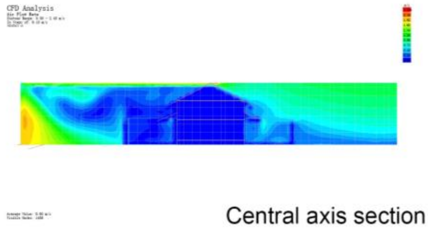
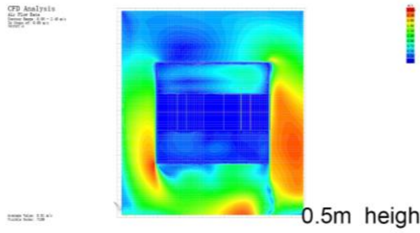
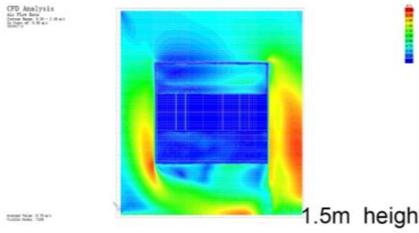
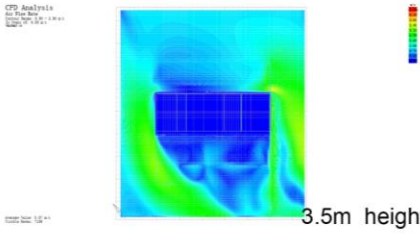


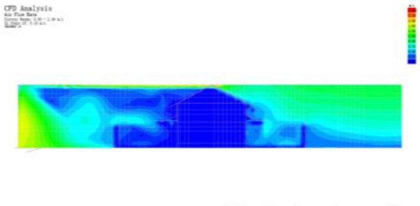
Central axis section

7m

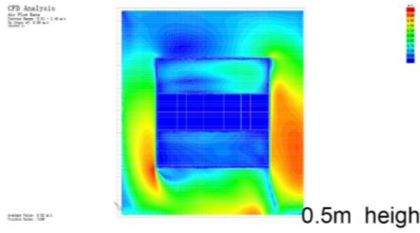

0.5m height


1.5m height


3.5m height


Central axis section

8m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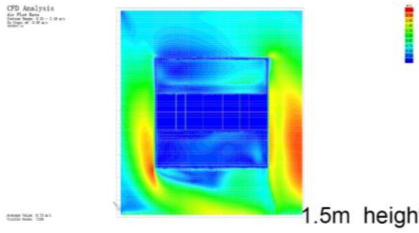
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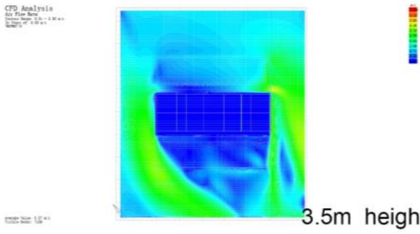
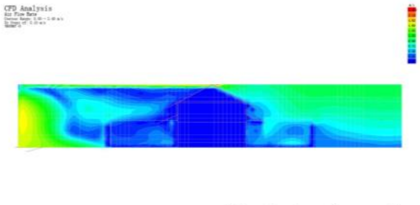
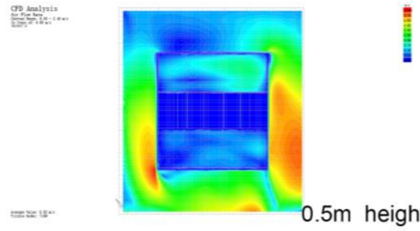

3.5m height


Central axis section

9m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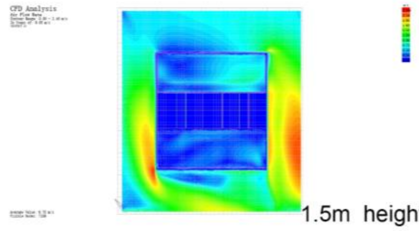
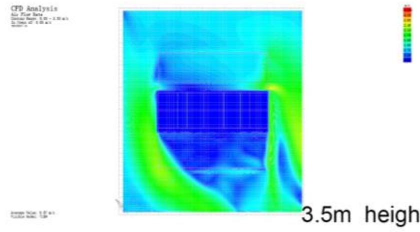

1.5m height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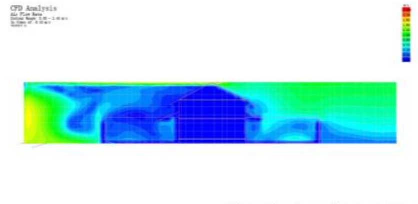

Central axis section

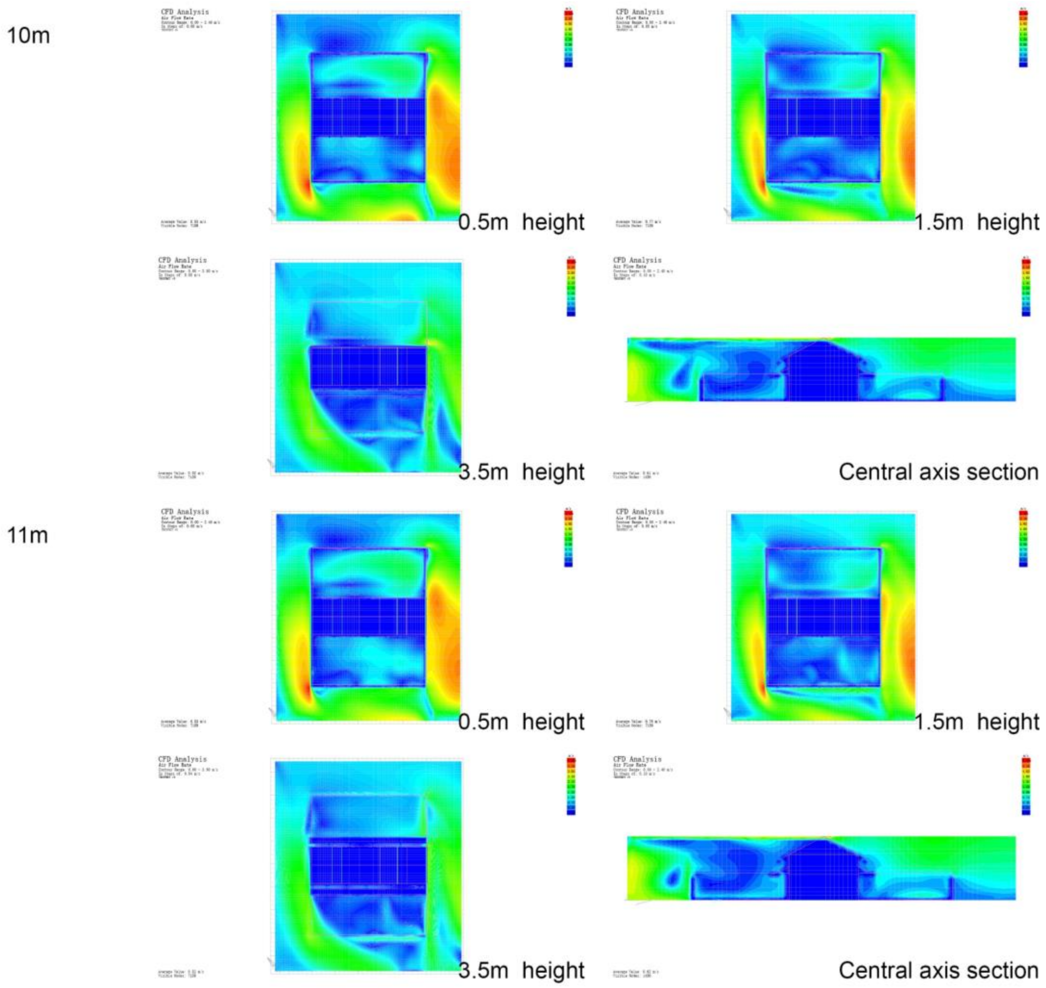


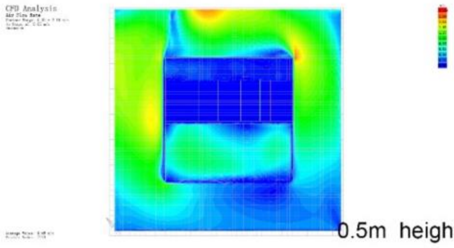
Figure 5-12. Wind velocity of Yan's public granary at different courtyard widths in winter.

5.4.3. Effect of different eaves widths on wind velocity

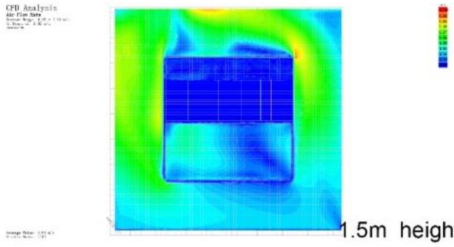
According to the simulation results, the width of the second-floor eaves has a greater impact on wind velocity than the width of the first-floor eaves. The winter simulation results indicate that with a constant width of the second-floor eaves, the average wind velocity in both courtyards weakens noticeably at 0.5m and 1.5m heights when the width of the first-floor eaves increases, but has less effect on the wind velocity at 3.5m heights. When the first-floor eaves are kept at a constant width, the average wind velocity increases in the back courtyard at 0.5m and 1.5m heights and has less effect on the wind velocity in the front courtyard as the width of the second-floor eaves increases. It also increases in the front courtyard at 0.5m and 1.5m heights but has less effect on the wind velocity in the back courtyard.

When the width of the second-floor eaves is constant and the width of the first-floor eaves is small, wind vortexes form in the front courtyard. However, as the eave’s width increases and prevents the formation of wind vortices, the wind velocity under the first-floor eaves reduces. As the first-floor eaves width increases, the back courtyard expands the area under the eaves, and the wind velocity decreases, which results in a lack of airflow. As the width of the first-floor eaves increases, the wind velocity in the space between the first and secondary eaves likewise decreases noticeably and air circulation lowers, and this trend is even more pronounced in the front courtyard. When the width of the first-floor eaves remains the same, the increase in the width of the second-floor eaves hinders the flow of air, which causes a considerable reduction in wind velocity between the first-floor and second-floor eaves.

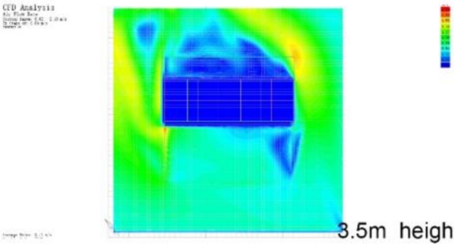
0.5m



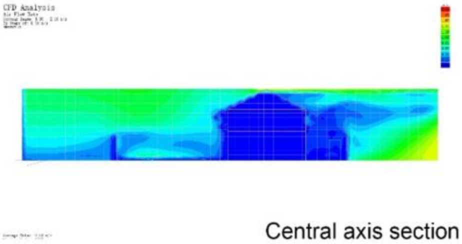
0.5m height



1.5m height

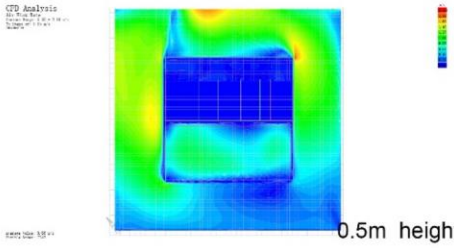


3.5m height

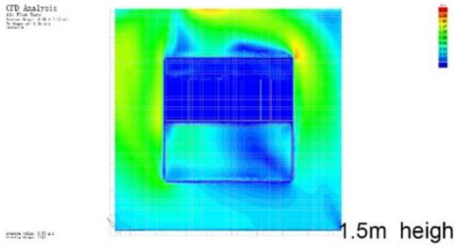


Central axis section

1.0m



0.5m height



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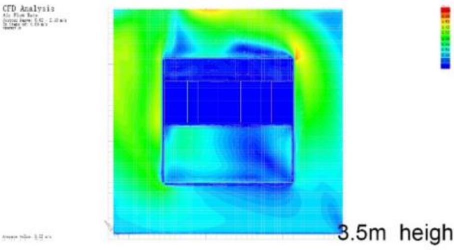
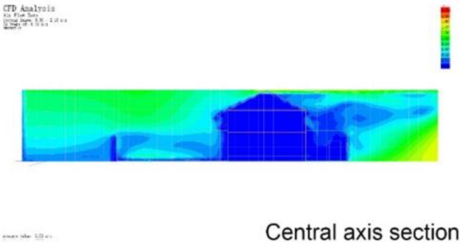
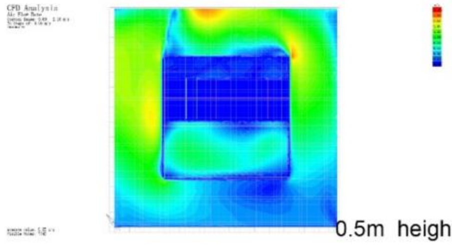


3.5m height



Central axis section

1.5m



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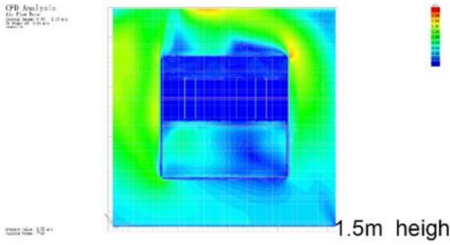
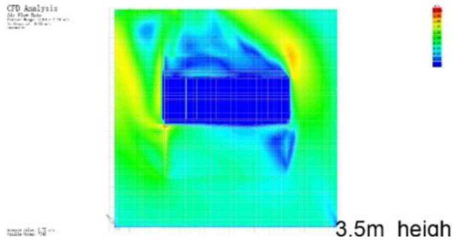
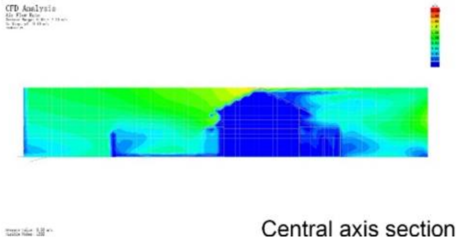


1.5m height



3.5m height



Central axis section

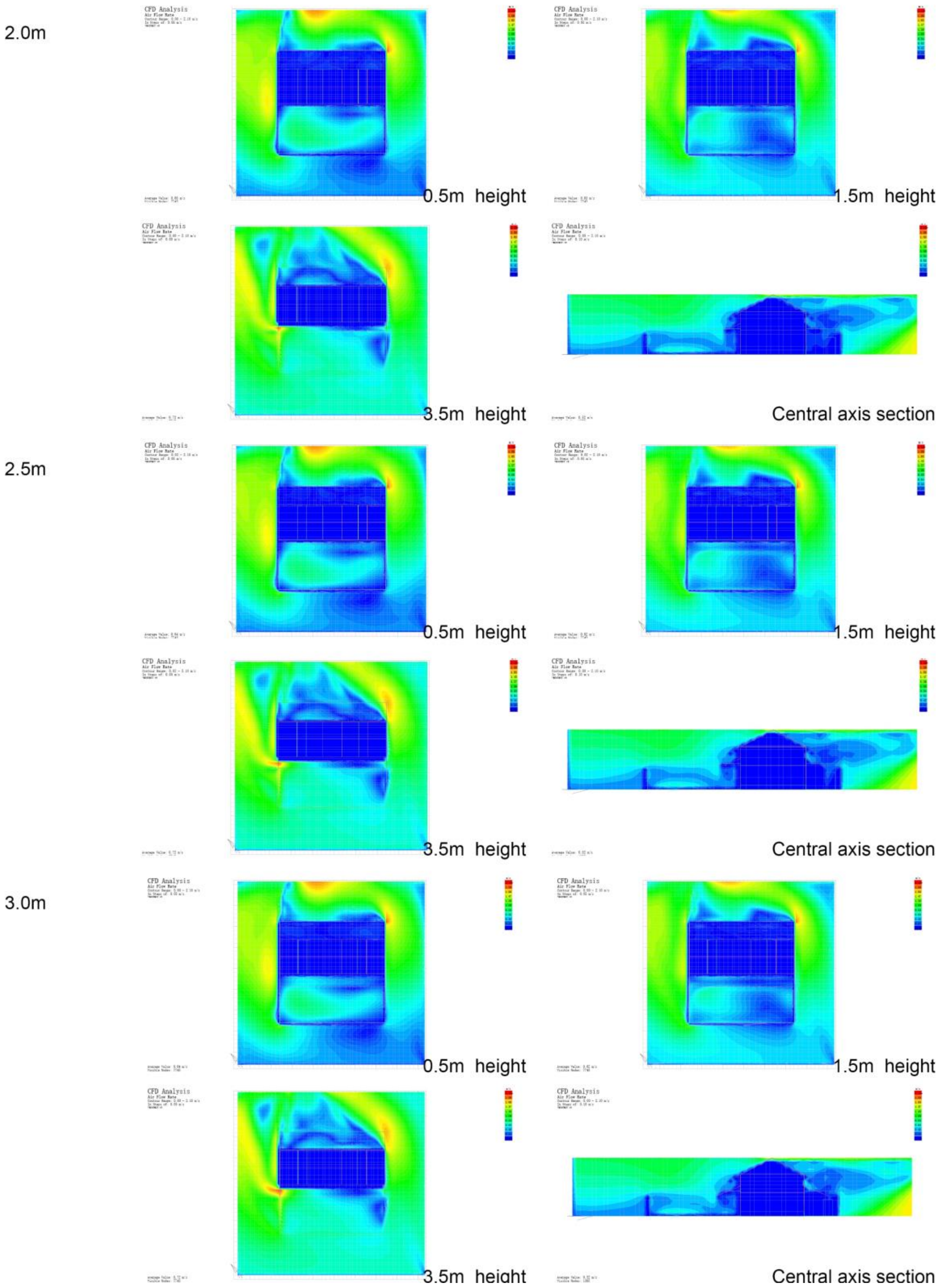
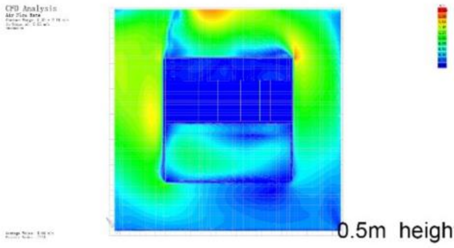
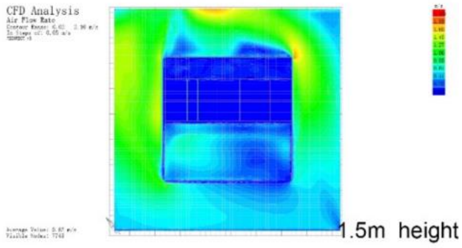


Figure 5-13. Wind velocity at different first-floor eaves widths in summer.

0.5m



0.5m height



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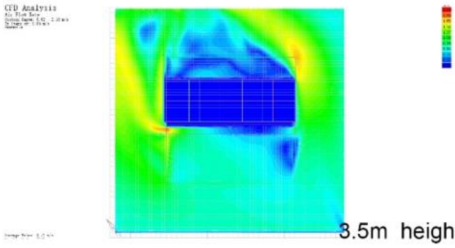
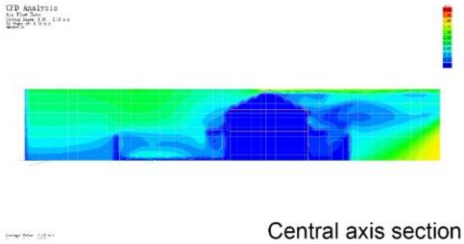
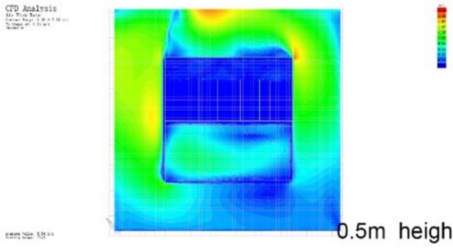


3.5m height

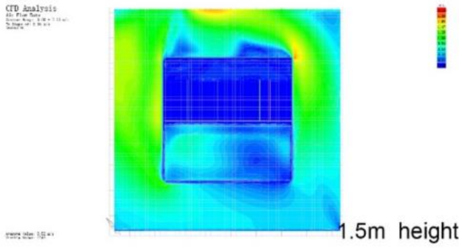


Central axis section

1.0m



0.5m height



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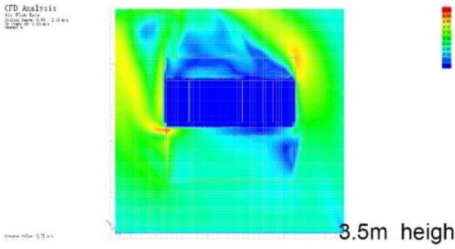
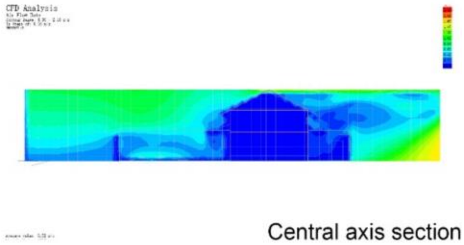
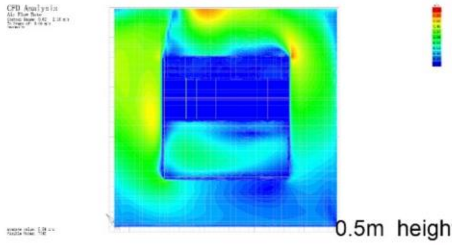


3.5m height

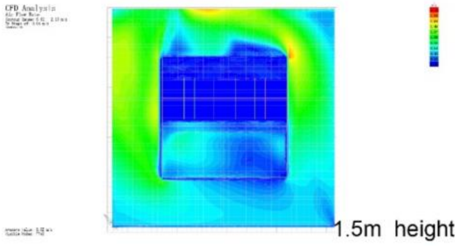


Central axis section

1.5m



0.5m height



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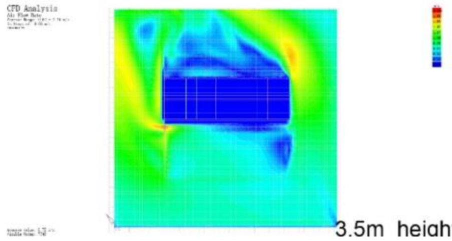

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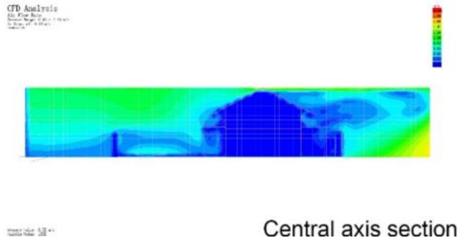


Central axis section

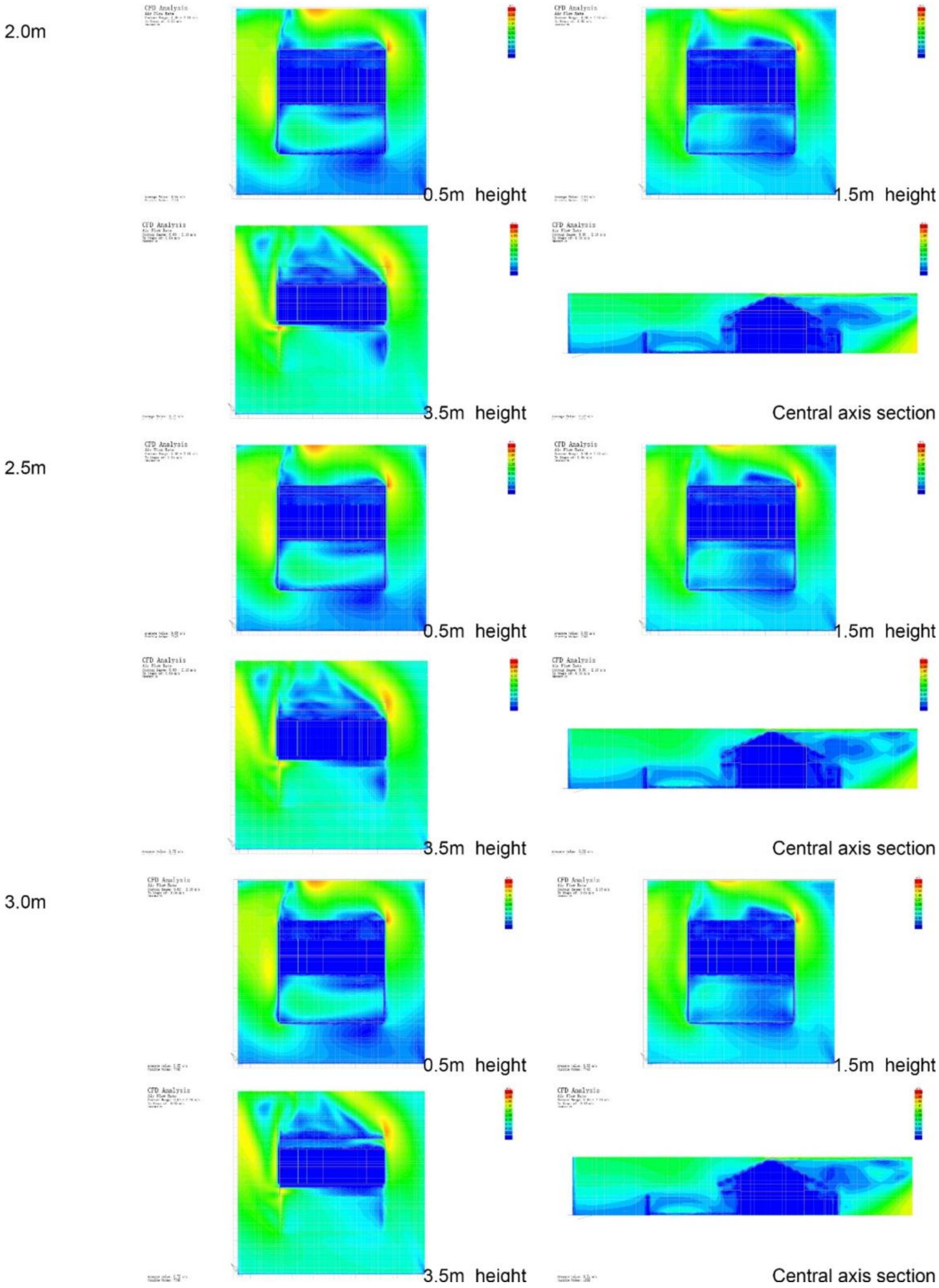
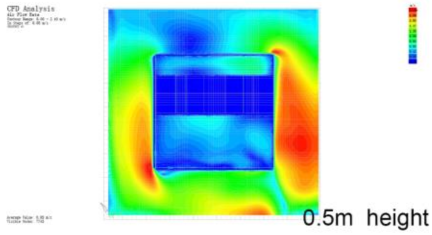
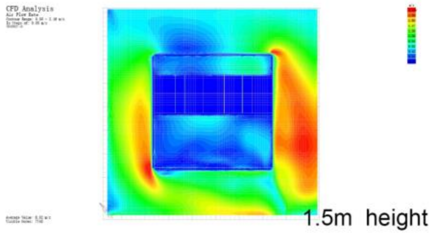


Figure 5-14. Wind velocity at different second-floor eaves widths in summer.

0.5m



0.5m height



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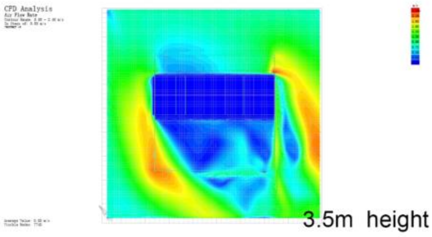

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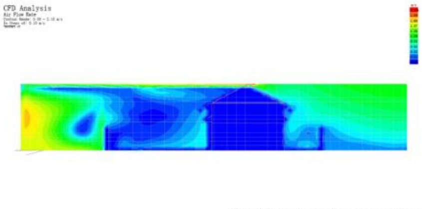
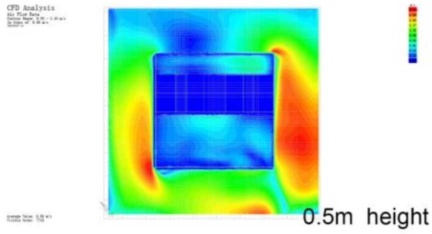


Central axis section

1.0m



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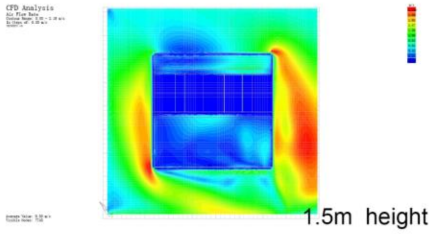

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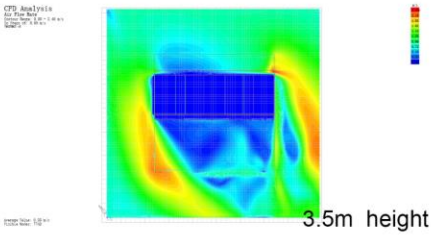

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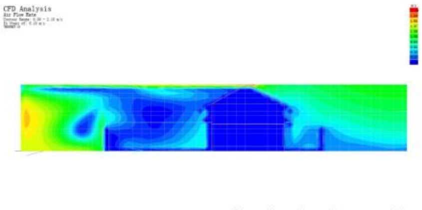
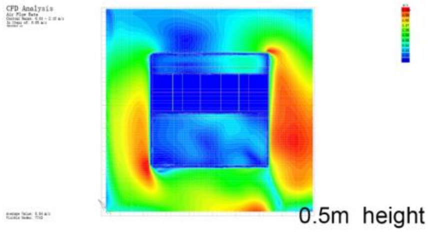


Central axis section

1.5m



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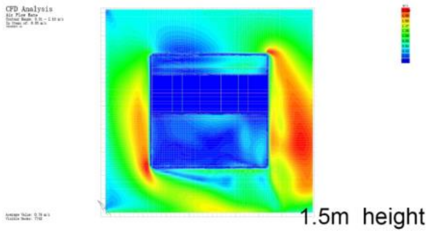

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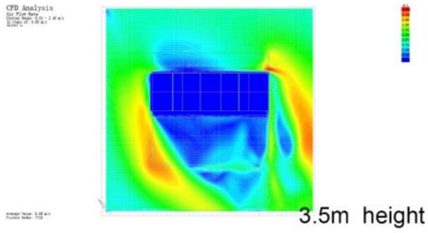

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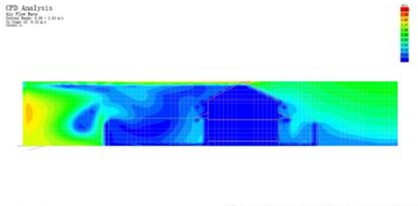


Central axis section

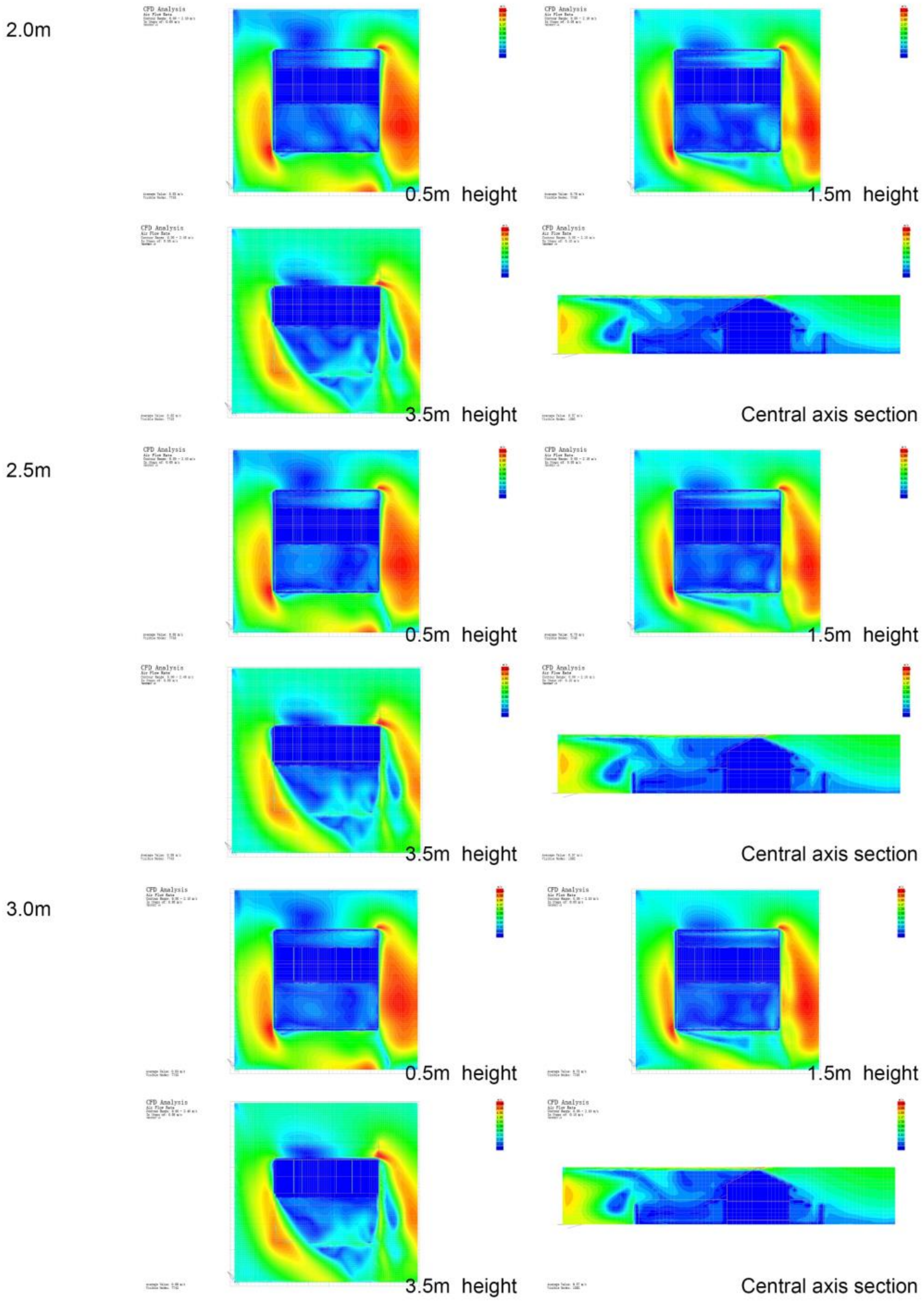
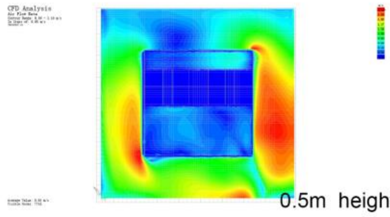


Figure 5-15. Wind velocity at different first-floor eaves widths in winter.

0.5m



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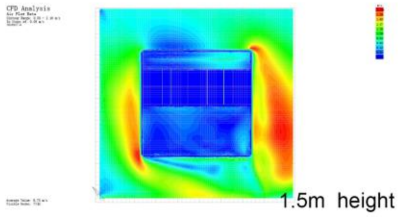
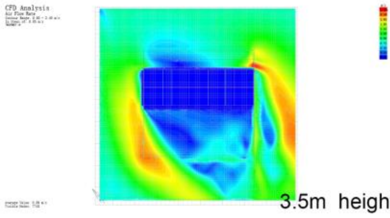


1.5m height



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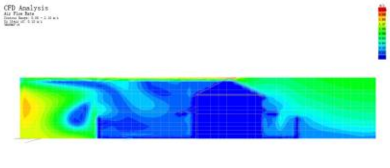
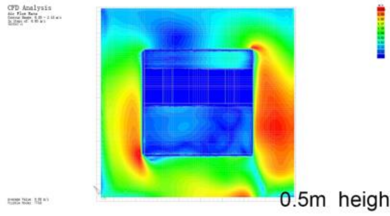
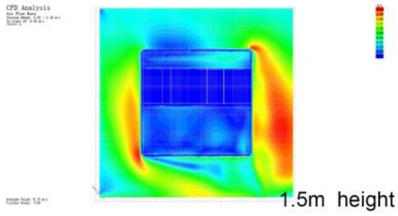


Central axis section

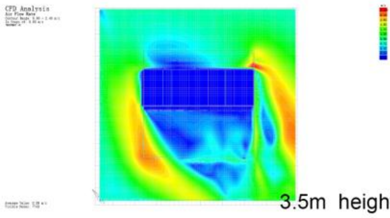
1.0m



0.5m height



1.5m height



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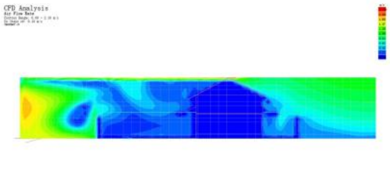
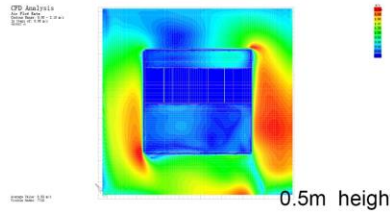
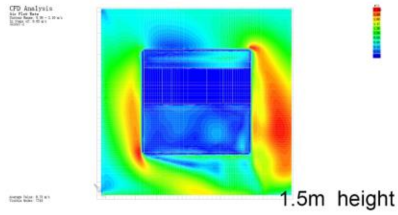


Central axis section

1.5m



0.5m height



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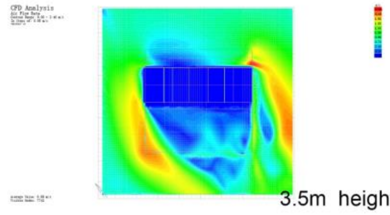

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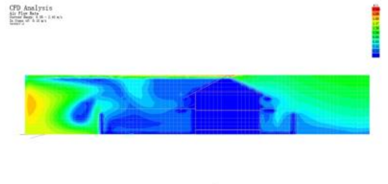

Central axis section

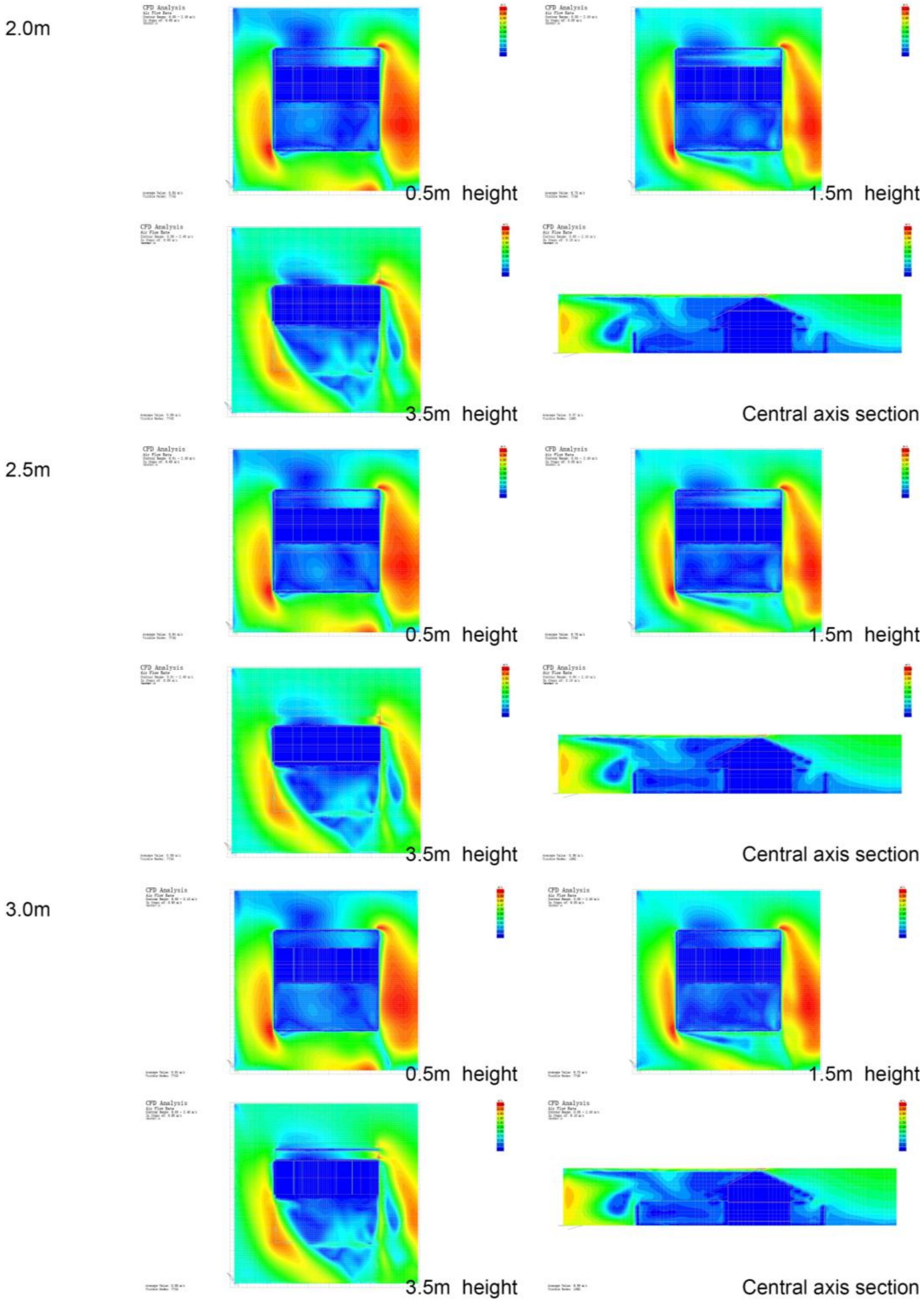

Figure 5-16. Wind velocity at different second-floor eaves widths in winter.

6. Discussion

The primary purpose of the design and construction of residential buildings is to meet the needs of the people living in them. People's requirements for living space go beyond the basic functional requirements such as rest, living, and activity. They also have needs for the comfort of the physical environment of the building. Technology is frequently used in modern architecture to make living spaces more comfortable, but this greatly increases energy consumption during the use of the building. The design and construction of traditional courtyard houses, on the other hand, minimises energy consumption while in use by actively using local climatic conditions and creating living spaces that satisfy the requirements for comfort in accordance with local cultural and social conditions.

6.1. The ancient philosophical concept the unity of man and nature

Culture is also a crucial component of the discussion on the sustainability of traditional architecture, and therefore the transmission and development of the ancient philosophical concept that the unity of man and nature are included in the discussion. For the purpose of understanding the link between ancient philosophical concept and building climate adaptation strategies, ancient philosophical concept along with the comfort of the building environment are analysed in conjunction.

The Chinese have a continuous pursuit of harmony, they believe that man and nature are interdependent and cannot exist separate from nature. Traditional Chinese architecture emphasized the harmonious co-existence and mutual promotion of man, architecture and nature, thus forming a harmonious and unified organic unity. Building climate adaptation strategies emphasise the creation of architectural forms and technologies that are adapted to and make use of the local environment and climate, based on an understanding of the local climate, with the aim of improving the environment in which buildings are used. The site, form and structure of the Yan's courtyard complex have all been designed according to the local climatic environment. For example, the Yan's courtyard complex has adopted measures such as introducing courtyards, roof shading and improving the thermal insulation of the envelope to cope with the local hot summer, cold winter and humid climate and to improve the usage environment of the buildings. The co-existence of man, buildings and the natural environment is the main objective of the building climate adaptation strategy.

Climate adaptation strategies are consistent with the idea of the unity of man with nature, that is, they both emphasise the relationship between humans and nature. Everything comes from nature and thus man, buildings and nature should be interdependent; man and buildings cannot exist without nature. The abstract philosophical idea of the unity of man with nature is carried in the form of climate adaptation strategies, which are generated by adapting to local natural conditions in the process of inheriting the philosophical idea. In addition, the harmonious interaction between the concept of unity of man with nature and climate adaptation strategies contributed to the enhancement of the use environment of traditional buildings and resulted in positive and effective sustainable solutions for buildings.

6.2. Climate response objectives

6.2.1. Heat protection in summer and warmth in winter

Ningbo's climate is featured by hot summers and cold winters. Moreover, the field monitoring results demonstrate that the temperature rise is less in winter compared to summer, which may be affected by the reduced hours of sunlight in the winter. Moreover, based on the solar radiation outcomes for the three buildings, both indoors and in the courtyard, the solar radiation received in winter is much less than in summer, thus recommending that buildings in Ningbo require to lose heat in summer and gain heat in the winter. On the other hand, the summer and winter solar radiation results tend to be consistent, with interiors or courtyards that receive more solar radiation in the summer also typically receiving more solar radiation in the winter. This contradicts the goal of heat reduction in summer and heat increase in the winter, and a combination of strategies is required to resolve this contradiction.

The study's findings are consistent with other research in that traditional structures are significantly more comfortable in the summer than in the winter (Gou *et al.*, 2015; Xu *et al.*, 2016; Juan *et al.*, 2019). In summer, the three buildings can fulfil the thermal comfort requirements in the evening and only a few hours of the day. Wintertime internal temperatures in all three buildings fall below the threshold for thermal comfort. This reflects that without advanced mechanical equipment, the interiors of the traditional courtyard houses hardly fulfil the thermal comfort requirements in the winter.

The indoor temperature and humidity of the three buildings in the summer and the humidity in the winter fluctuate lower than the corresponding courtyard and outdoor parameters, and the maximum and minimum indoor temperatures of the three buildings in winter are higher than the maximum and minimum outdoor temperatures, respectively, and fluctuate less than the corresponding courtyard temperatures. This shows that the external envelope of traditional houses holds an excellent thermal insulation capacity and can maintain a specific degree of constant indoor temperature and humidity. Based on the thermal resistance calculations of the walls, the hollow brick walls of Yan's courtyard complex contain better thermal insulation properties and hold the benefits of saving bricks, sound insulation, and moisture resistance. This is in line with Fang Ling's findings (2013) that the blue brick hollow bucket walls have more thermal resistance and better insulation properties. By filling the hollow brick wall with yellow mud, the thermal resistance of the wall is enhanced and resultantly, the thermal insulation performance is improved. This reflects that selecting appropriate suitable material to fill the cavity of a hollow brick wall can put a great influence on the thermal insulation performance of the wall. In conclusion, the thermal performance of the wall is significantly influenced by both the material choice and the masonry process. Based on the thermal resistance calculation of the roof, tile roofs hold an excellent thermal insulation capacity. The air layer built between the tiles stops direct sunlight during the day and does not stop ventilation and heat dissipation between the interior and exterior. Moreover, the thermal insulation of tile roofs rises significantly with the addition of a layer of straw mats removed with ash and clay.

Based on the simulations of the solar radiation of the building, the solar radiation indoors is much less than that of the courtyard, reflecting that the building envelope effectively blocks the solar radiation from transferring heat. To create a more comfortable thermal environment, it is advised that people spend more time indoors in the summer and additional time in the courtyard in the winter to be able to get a more comfortable thermal environment. This is aligned with the research of Apolonio Callejas et al. (2020). Based on the simulation results for the interior, solar radiation is always more indoors near the doors and windows, and thus, solar radiation enters into the interior mainly from the doors and windows.

Solar radiation simulations for the three buildings demonstrate that the first floor of a building almost always gets more solar radiation than the second floor, rather than the existence of eaves on the building. Rooms, having south-facing windows and doors, tend to get higher solar radiation, while rooms with north-facing windows and doors get less solar radiation, aligned with the traditional Chinese idea of sitting in the north and facing the south. The three buildings experience much greater indoor and courtyard solar radiation when the eaves are absent, demonstrating that the eaves are more effective in providing shade. In contrast to the solar radiation received by the three buildings without eaves, the granary gets more solar radiation, mainly because of the larger window-to-wall ratio and the larger width-to-deepness ratio of the building.

On the basis of solar radiation simulations for various courtyard widths, wider courtyards typically enable the building to receive more solar radiation to be received by the building. The amount of solar radiation received by the courtyard and the interior in summer and winter reduces as the eaves' width grows, according to simulations of solar radiation with various eaves widths. Although the eaves are efficient in blocking solar radiation, the width of the eaves cannot be enhanced indefinitely in order to avoid too little solar radiation being received by the interior in the winter.

6.2.2. Moisture and rain protection

The coastal and subtropical monsoon climate results in Ningbo being a wet and rainy city, so moisture and rain protection is a key local climate adaptation objective.

To adapt to the rainy environment of Ningbo, the design and construction of Yan's courtyard complex emphasised moisture and rain protection. All three buildings in Yan's courtyard complex are around 10 cm more than the courtyard to stop rainwater from spilling into the interior and the base of the exterior walls are comprised of stone to prevent rainwater erosion. In order to promote the flow of rainwater and endure the influence of the rain over time, the roofs are sloped and the roof tiles are strong and long-lasting. The roof slopes towards the courtyard and the eaves go beyond the walls to stop rainwater from eroding the walls. Rainwater runs off the roof and into the courtyard, where it is quickly drained by hidden gutters. Moreover, there are water tanks in the courtyard to collect rainwater and promote water recycling. In order to minimise dampness, the ground floor of Yan's public granary was elevated by 0.57m to build an elevated floor, and ventilation openings were installed on the elevated floor's walls. The elevated floor's smooth air circulation allows some of the heated and humid air to be carried away by internal airflow, which reduces the impact of humidity and facilitates heat and moisture dissipation. Also, the envelope resists moisture well. The air layer of the hollow brick wall protects the humid air and keeps the interior dry. The roof contains gaps between the tiles to allow air circulation and remove humid air. In contrast to humidity indoors, outdoors, and in the courtyard demonstrates that the humidity fluctuates less indoors and is lower humid than outdoors, therefore, demonstrating the effectiveness of these measures to prevent rain and moisture.

To summarise, the ancients used a variety of strategies to adapt to the rainy and humid climate of the region and they were effective.

6.2.3. Daylighting

Traditional buildings can only get a limited amount of light because sunlight serves as the primary source of light when mechanical lighting is not used.

The Yan's courtyard complex is a building of the Yan family funded by Mr. Yan Kangmao, so all three of these buildings are classified as residential buildings in this dissertation for analysis purposes. According to the Standard for Daylight Design of Buildings GB50033-2013, the light in bedrooms and living rooms (halls) of residential buildings should not be lower than the standard value of light for light level IV. The daylight factor of rooms with side lights should not be lower than 2.0%, while the natural indoor daylight illuminance should not be less than 300 lx. Residential buildings should have direct lighting in the bedrooms, living areas (halls), and kitchens.

The average daylight illuminance on the first floor of Yan's former residence is 223.29 Lx, with an average daylight factor of 1.65%. On the other hand, the average daylight illuminance on the second floor is 151.58 Lx, with an average daylight factor of 1.12%. The Yan's Ancestral Hall has an average daylight factor of 1.38% and an average daylight illuminance of 186.44Lx. The average daylight illuminance on the first floor of Yan's public granary is 308.9Lx and has an average daylight factor of 2.29%; whereas the average daylight illuminance on the second floor of Yan's public granary is 89.71 Lx, and the average light factor of 0.66%. Although direct daylighting is present in all three of the buildings in the Yan complex, only the first floor of the public granary has an average daylight illuminance and an average daylight factor that are in compliance with code requirements.

In general, the interior lighting environment of Yan's courtyard complex is comparatively poor. The simulations show that the building receives more light in the parts of the building near the doors and windows, which is due to the fact that the daylight comes mainly from the sun's rays through the windows and doors. The ground floor of Yan's public granary has a higher window-to-wall ratio, which could be the reason for its brighter light. This indicates that a larger window-to-wall ratio increases the amount of light received in the room.

When simulating a situation without eaves for shading, the improvement in the indoor lighting environment of the three buildings is noticeable. The average daylight factor of Yan's ancestral hall, the first floor of Yan's public granary, and the second floor of Yan's former residence can fulfil the code requirements. While the average daylight illuminance of Yan's ancestral hall, as well as the first floor of Yan's public granary, can meet the code requirements. The eave is a crucial factor impacting the indoor lighting environment, as they block solar radiation as well as the daylight entering the buildings. Based on simulations of the lighting environment for various eaves widths, the daylight illuminance and daylight factor of the interior decrease dramatically as the width of the eaves increases. However, this trend is less pronounced when the eaves exceed a certain width. With only the lighting in focus, the narrower the width of the eaves, the better.

According to the analysis, buildings facing south will receive better light, but since this experiment is based on an all-overcast model, simulating the effect of building orientation and location on natural light is not possible. On the basis of the simulation of the lighting environment at various courtyard widths, it is found that expanding the width of the courtyard is effective in increasing the light in the building. The wider the courtyard, the better the interior lighting when only daylighting is taken into account.

In general, the interior lighting environment of Yan's courtyard complex is poor. The window-to-wall ratio, orientation, eave width, and courtyard width all have an effect on the lighting environment of the building, with the window-to-wall ratio and eave width being the most significant.

6.2.4. Ventilation

The local climate is hot in summer and cold in winter. Local meteorological data and simulation results highlight that the local wind is more prevalent in the summer from the south-east and in winter from the north-west, so making use of the south-east wind to increase ventilation in summer and paying attention to the north-west wind protection in winter is essential.

Apart from influencing the perception of the wind environment, ventilation can also carry away a certain amount of heat and have an impact on the thermal environment. Based on the overall wind environment simulation for the three buildings, it can be observed that the wind velocity in the courtyard in winter is significantly lower in comparison to the wind velocity outside, and the building effectively hinders the reduction in temperature owing to ventilation. In summer the wind velocity in the courtyard is low, which does not facilitate the elimination of heat by ventilation in summer. However, in general, the wind velocities in the courtyards of the buildings satisfy the comfort requirements. The wind velocity in the street between the three buildings is also less than 2m/s, which is acceptable for human comfort.

The width of the eaves and the width of the courtyard both affect the wind velocity inside the courtyard. The wider the courtyard, the greater the wind velocity and the better the air circulation within the courtyard. The wind speed in the courtyard at first and second-floor heights is influenced by the width of eaves on the first floor. The width of the eaves on the second floor does not significantly affect the wind velocity at first floor height, but generally the wider the eaves, the lower the wind velocity in the courtyard.

Overall, the wind velocity of Yan's courtyard complex meets the requirements for human comfort, with less heat being carried away by ventilation and heat dissipation in both winter and summer.

6.3. Coordination of climate adaptation strategies

Different climate adaptation strategies have consistent or different effects on the thermal, light, and wind environments of buildings, which can lead to conflicts between climate adaptation strategies and climate adaptation objectives. For instance, eaves blocking direct summer sunlight satisfy the heat reduction requirement in summer, but also blocks solar radiation in winter, when the purpose of climate response is to obtain more solar radiation. Climate adaptation strategies should therefore be taken into account in an integrated manner so as to achieve climate response objectives. Research has demonstrated that the orientation of the building, the envelope, the window-to-wall ratio, the width of the eaves, and the courtyard width all influence the physical environment of the building.

The envelope primarily affects the thermal environment of the building, and the envelope of traditional courtyard houses has better thermal insulation properties. A proper window-to-wall ratio should be chosen because buildings with a large window-to-wall ratio receive more solar radiation and light, but too much solar radiation is bad for heat protection in summer. The wider the width of the courtyard, the more solar radiation the interior of the building receives, the more daylight illumination, and the higher the wind velocity in the courtyard. The wider the width of the eaves, the less solar radiation the building receives indoors, the less daylight illumination, and the lower the wind velocity. When determining the width of the courtyard and eaves, it is critical to consider both summer heat reduction and winter insulation, lighting, ventilation, and economy.

7. Conclusion

Over time, traditional Chinese courtyard houses have evolved as they have adapted to the local culture, climate and environment. Historic culture and adaptation to the climatic environment are two key aspects of a sustainable approach to the study of courtyard houses. Climate response strategies of traditional courtyard houses in Ningbo with hot summers, cold winters, and humid climates are examined in this study. Traditional courtyard houses in Ningbo are important cultural heritage because they preserve the historical memories of the local people and serve as important cultural symbols. The Yan's courtyard complex has common characteristics of local courtyard houses and was thus chosen as a case study. This was done in order to assess the effective climate adaptation strategies adopted by traditional courtyard houses and to identify sustainable approaches to modern architecture in terms of historical culture and adaptability to the climatic environment. Field research and site measurements were carried out on Yan's courtyard complex, and the thermal, light, and wind environments of the interior and courtyard were simulated by software. The following are the key findings.

(1) The unity of man with nature is the primary view of the ancient philosophical concept. The ancient Chinese revered nature and hold the opinion that they were closely related. It was believed that even though man could occupy and make use of nature, they had to live in a way that was in harmony with it. The aim of the transformation of the world by man was to bring about the peaceful coexistence of man and nature.

(2) There is an essential consistency between the ancient philosophical concept of the unity of man with nature and climate adaptation strategies. The ancient philosophical concept of the unity of man with nature has greatly influenced the philosophy and practice of traditional Chinese architecture. This idea is represented in architecture, which implies that the local climate and natural conditions should be respected in the practice of architecture in order to achieve harmony between the comfort of the user and the environment. To prevent the severe local temperature and environment from having an impact on the living environment, climate adaptation places an emphasis on the rational use of local natural resources as well as the use of technology. It can be said that climate adaptation strategies are a concrete practice of the environmental concept of the unity of nature and man.

(3) In order to improve the comfort of living spaces, ancient builders utilised a variety of climate adaptation strategies in Chinese traditional courtyard houses. The weather in Ningbo is hot during the summer, cold during the winter, and rainy and humid all year round. Consequently, protection from heat in the summer and cold in the winter, from moisture and rain, ventilation, and enough daylighting are the key climatic adaptation objectives for the area. In the absence of cutting-edge technology, traditional courtyard houses often make use of appropriate climate adaptation strategies for building form generation and material selection for creating and enhancing a comfortable living environment. Traditional courtyard houses may adapt to harsh climates and

provide their occupants with suitable living spaces with the help of climate adaptation strategies. This paper concludes the climate adaptation strategies adopted by the local traditional courtyard houses so as to realise their climate adaptation goals, including the choice of site to hide wind, gather qi and obtain water, south-facing orientation, courtyard plan, and courtyard width, shading of the eaves, construction of the envelope, appropriate door and window ratios, air layer under the floor, human habitation, water recycling and the idea of land conservation. The impact of climate adaptation strategies varied depending on the goals of the strategy, so the impact of these strategies on different indoor physical environments needs to be analysed and considered together.

(4) In terms of climate adaptation strategies, this dissertation looks at the impact of climate adaptation on the thermal, lighting, and wind environments of Yan's courtyard complex. An adaptive model is employed in this dissertation to evaluate the thermal comfort of Yan's courtyard complex in both the summer and winter. According to the thermal comfort criteria, the thermal comfort requirements are met at night and part of the day in summer, whereas the comfort requirements are not met in winter when the rooms are too cold. The results of the field monitoring indicate that the degree of temperature and humidity fluctuations in the three buildings is smoother compared to fluctuations between the courtyard and the outdoors and that the differences in indoor temperature and humidity between the three buildings are not significant. A key factor in establishing thermal comfort indoors is the insulation of the envelope. The hollow brick walls and tiled roofs of Yan's courtyard complex both have good thermal insulation, reduce indoor heat gain in summer and lower heat loss in winter, and have good moisture resistance. The courtyard house was enclosed and did not open to the external street in cultures that distinguished between it and the external street. The courtyard, however, allowed the building to open its windows towards it, increasing solar radiation, natural light, and ventilation inside the complex. In summer, the eaves reduce the solar radiation received by the interior, improving the comfort of Yan's courtyard complex, nevertheless, the eaves also reduce the natural daylight received by the building and reduce the wind speed in the courtyard, so the width of the eaves should not be too wide. In order to produce a comfortable atmosphere in the winter, a south-facing building, a suitable window-to-wall ratio, significant insulation, and a large courtyard width are the options. A larger courtyard width not only allows for more solar radiation and daylight inside but also increases the courtyard's wind speed while reducing air pollution. People adapt dynamically to the local climate and can make the best possible use of climatic resources by opening windows and ventilating the space and utilising it dynamically in various seasons. In short, the traditional architecture makes active use of climatic resources while putting great emphasis on negative climatic influences as well.

The climate adaptation strategies put forward in this dissertation can aid in maintaining and preserving traditional houses in hot-summer, cold-winter, and humid regions; in addition, the climate adaptation methods in this study can also serve as a reference for the study and preservation of traditional houses in other climatic conditions. The sustainable approach to traditional courtyard houses reaffirms the characteristics of the traditional house: it is adapted to the local environment, resources, climate, and culture and is constantly iterated, preserved, and inherited.

Traditional courtyard houses are vital historical and cultural heritage and this dissertation examines their climate adaptation strategies in order to get a better understanding of them. The dissertation examines the correlation between the ancient philosophical concept of the unity of man with nature and climate adaptation strategies; and suggests some of the climate adaptation strategies employed by traditional courtyard houses. These findings set a basis for the conservation of traditional courtyard houses and the advancement of modern architecture. Traditional courtyard homes offer a favourable experience that should be preserved and inherited in order to offer solutions for the sustainable development of modern architecture. The Yan's courtyard complex, as a typical representative of traditional courtyard buildings in Ningbo, provides some sustainable experience for local buildings. In terms of site selection, spatial form, building structure and materials, the Yan's courtyard complex is fully adapted to the local climate, environment and culture, adopting natural ventilation, sun shading, heat insulation and moisture-proofing to provide users with a good environment and embody the concept of sustainable development with low energy consumption. These climatic strategies can be used as a reference for contemporary building design and develop and refine them in combination with the characteristics of the times. The climate adaptation strategies used in the Yan's courtyard complex are seen as an effective way to reduce energy consumption. For example, the hollow brick wall filled with yellow mud have good thermal insulation to suit the cold winter and hot summer climate of Ningbo. The climate adaptation strategies of traditional courtyards are still valid today, and how these strategies can be passed on and integrated into modern architecture in an economical and effective way is the next research work to be discussed. However, the heritage and promotion of traditional courtyard buildings should not be limited to the technical aspects, it is also important to explore the cultural aspects in order to find culturally and technically sustainable solutions for the buildings. Buildings that have inherited the local culture show a strong vitality, allowing sustainable development to be achieved. The Yan's courtyard complex contains a profound idea of the unity of man with nature, and the idea that building, man and nature are a harmonious and unified whole should also be passed on and improved in the design and construction of modern buildings.

However, this study does have certain limitations. The field data was collected for only 10 days and no temperature and humidity data were gathered for the transitional seasons. The climate data used for the simulations were based on Dinghai, which is not quite close to Ningbo, and the Ecotect software did not allow for the setting of ventilation patterns for windows and doors. More long-term field measurements will be carried out in the future in conjunction with other simulation software to provide more reference information on contemporary building design.

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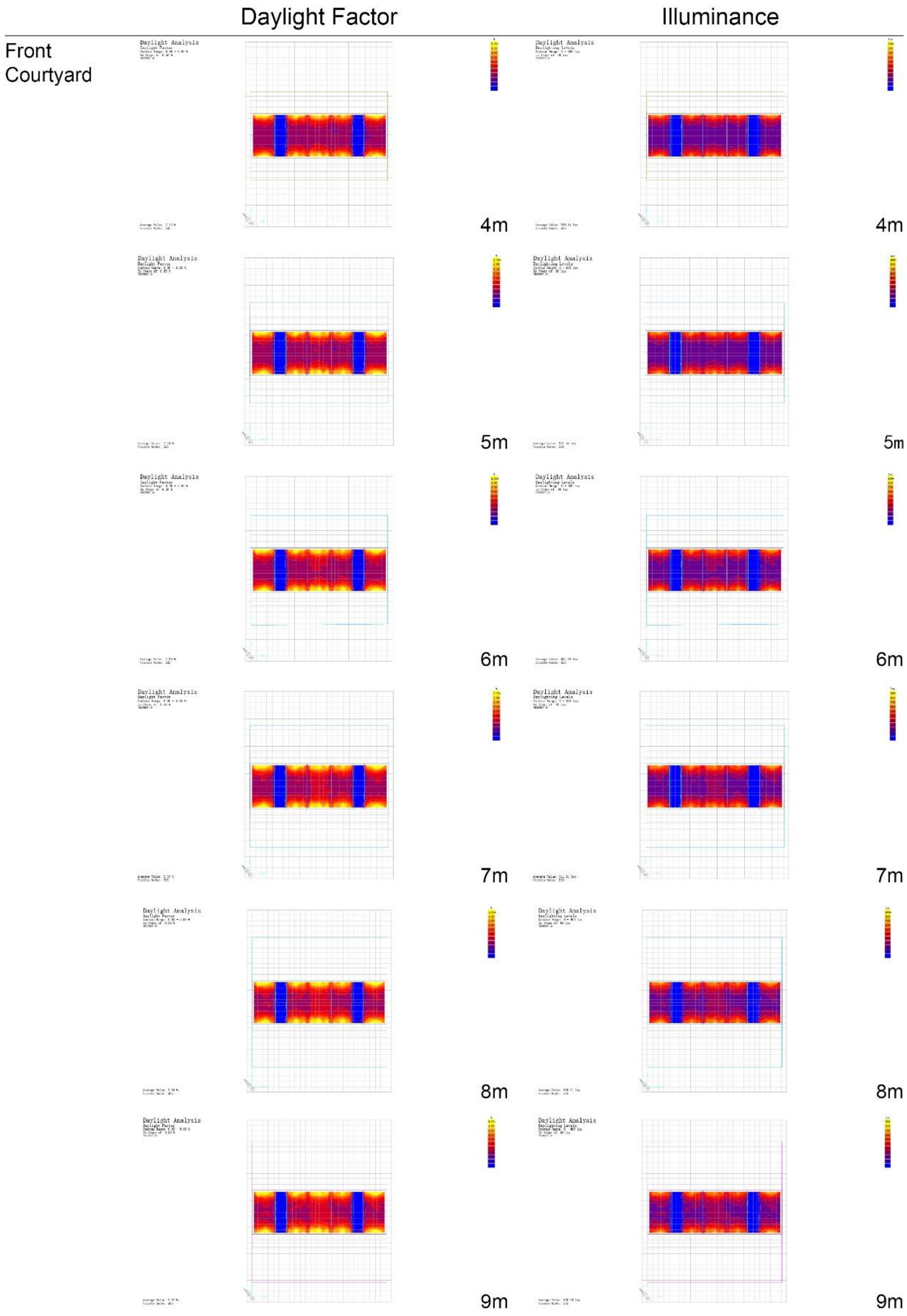
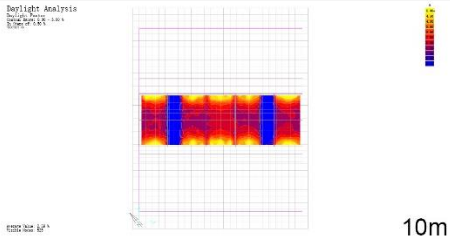
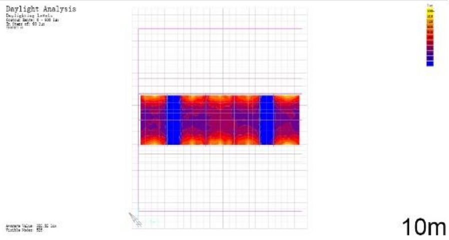
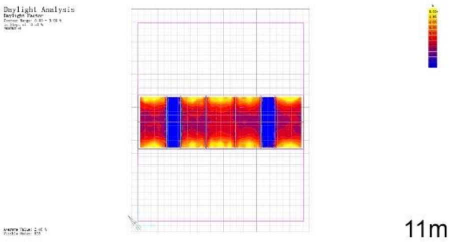
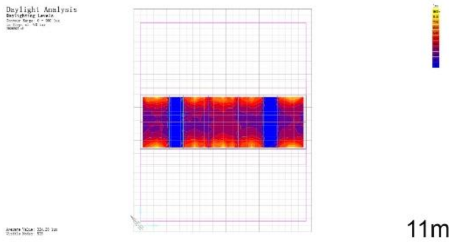
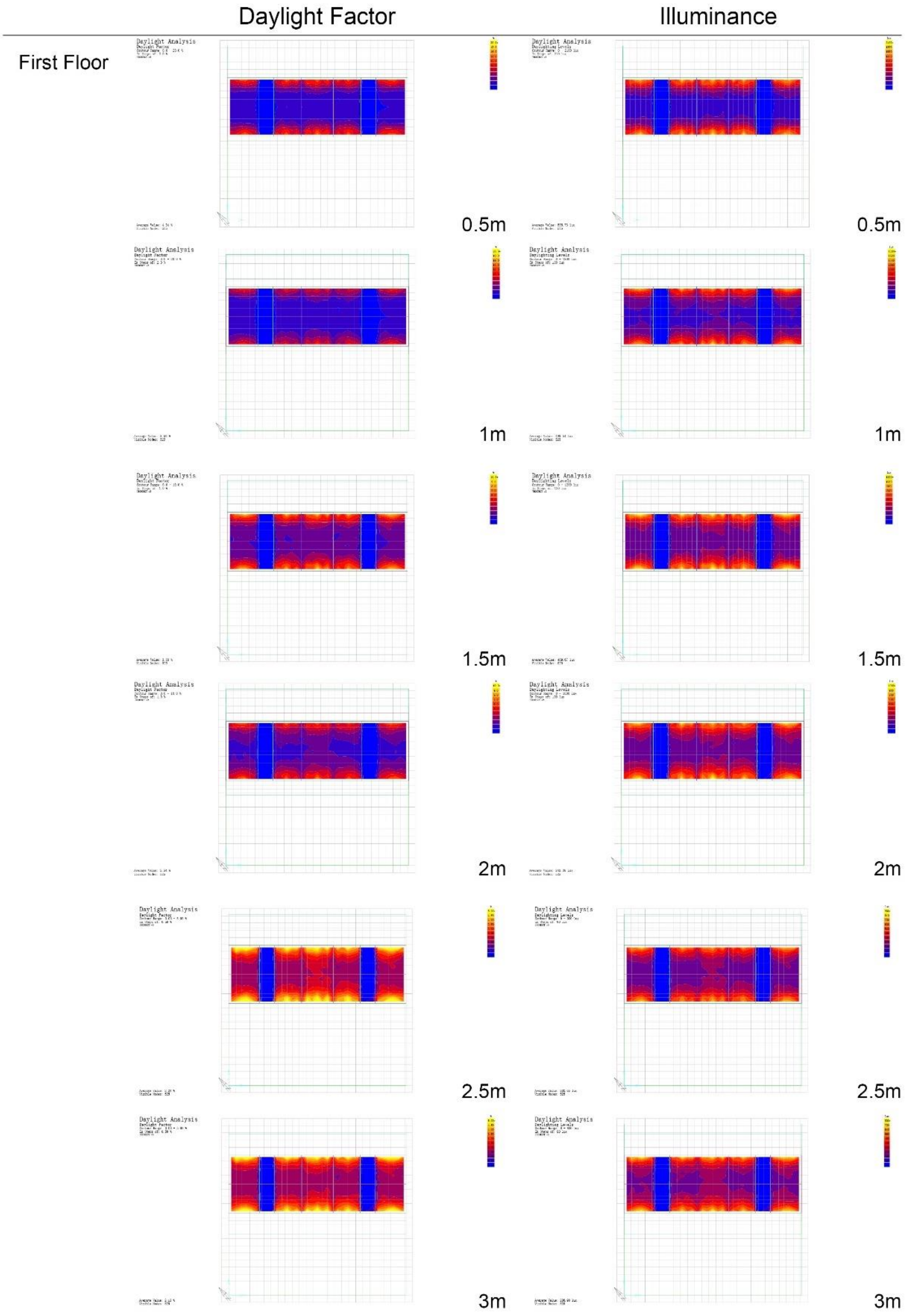
Appendix A: Daylighting factor and illuminance of Yan's public granary on first floor at different courtyard sizes.

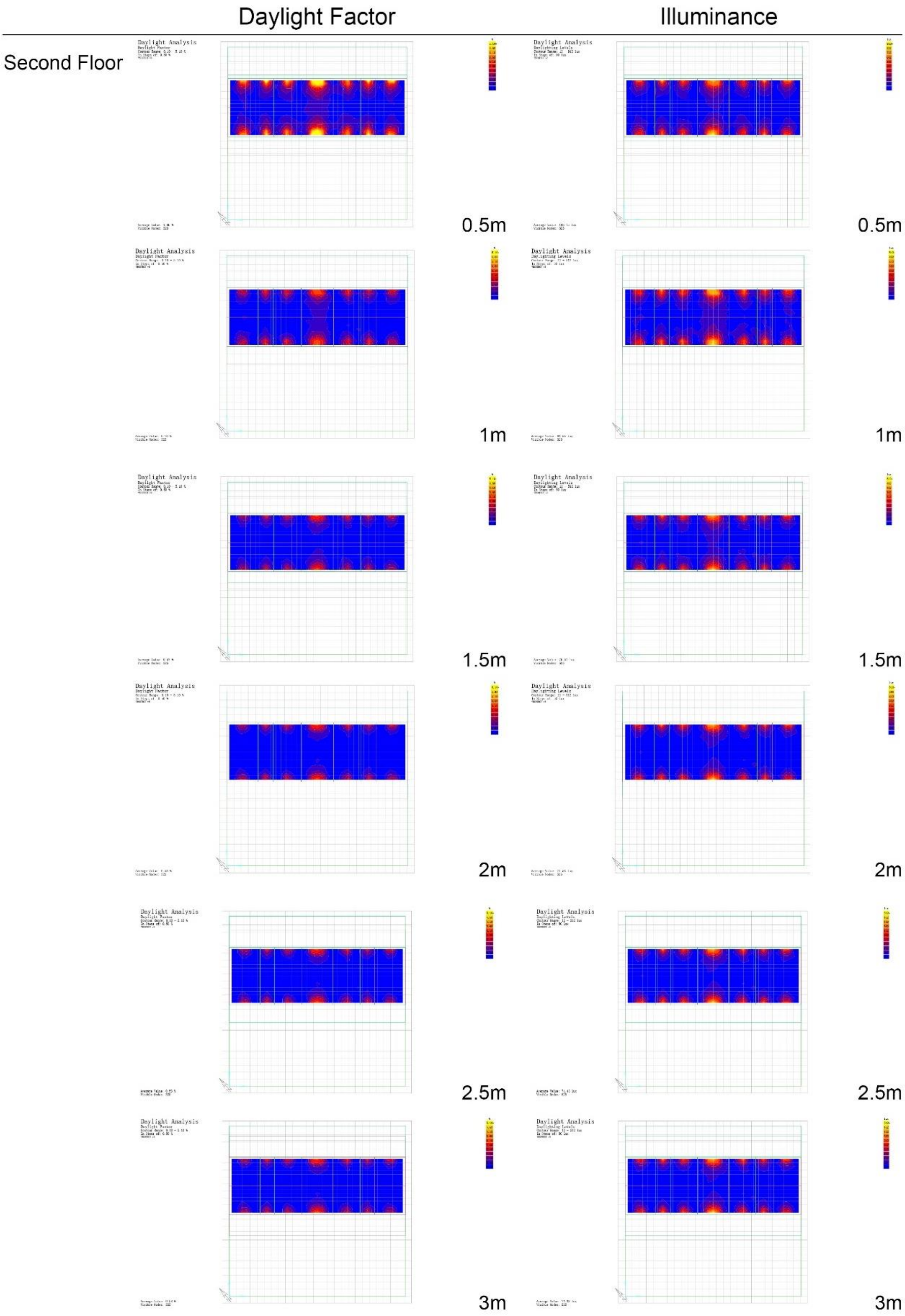


	Daylight Factor	Illuminance
Front Courtyard	 10m	 10m
	 11m	 11m

Appendix B: Daylighting factor and illuminance of Yan's public granary on first and second floor at different eaves widths.



a. Daylighting factor and illuminance of first floor at different first-floor eaves widths.



b. Daylighting factor and illuminance of second floor at different second-floor eaves widths.