IMPACTS OF CLIMATE CHANGE ON BUILDING PERFORMANCE AND ADAPTATION SOLUTIONS

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Abstract - Climate change has had significant impacts on the global climate, affecting the operational efficiency of buildings. This study employs future climate prediction methods based on the latest IPCC scenarios, using General Circulation Models (GCMs) to forecast climate conditions in three regions of Vietnam. Additionally, the study integrates simulation and simulation-based optimization methods to project the rise in greenhouse gas emissions and the level of thermal discomfort (overheating) in commercial buildings in Vietnam. The findings indicate that, due to the effects of climate change, carbon emissions from commercial buildings in Vietnam could increase by 6% to 22%, while the duration of overheating inside buildings may rise by several tens to several hundred percent.

Key words - Climate change; energy simulation; carbon emissions; commercial building; design solutions

1. Set the problem, necessity and significance of the research

According to the assessment report of the intergovernmental panel on climate change (IPCC) published in March 2023, the warming of the earth is very clear. The report of the Intergovernmental Committee on Climate Change stated: Climate change is happening faster than forecast. The report also proves that the earth's surface and sea surface temperatures have increased by more than 0.48 °C compared to the period 1961 - 1990; global sea levels also rose to a record high, reaching 3.2 mm/year, double the level 1.6 mm/year of the 20th century.

In Vietnam over the past 70 years, the average annual temperature has increased, on average 0.1 ºC/decade. The average temperature of the decade 1991-2000 in Hanoi was 0.7ºC higher than the average temperature of many years (1961-1990). Sea level observed at Cua Ong and Hon Dau stations over the past 50 years shows that on average each decade it has increased by 2.5-3.0 cm. According to research by the Australian Agency for Science and Industry for the Asia-Pacific region, it shows that: except for the Northwest, Viet Bac and Central Highlands, all other regions have increased temperatures corresponding to the years 2010 and 2050 and 2075 are 0.3, 1.1 and 1.5ºC respectively. The three remaining regions mentioned above had larger increases of 0.5, 1.8 and 2.5ºC.

According to the "2020 Climate Change Scenario" of the Ministry of Natural Resources and Environment of Vietnam, the highest and lowest temperature increase can reach 4.7°C and 4.1°C by the end of the century under the RCP8.5 scenario; By 2100, the average sea level rise for the entire East Sea region according to the RCP4.5 scenario is 56 cm (38 cm ÷ 78 cm) and according to RCP8.5 it is 77 cm (51 cm ÷ 106 cm). The average sea level rise along Vietnam's coast is likely to be higher than the global average sea level. Therefore, Vietnam ranks high in the group of countries most severely affected by the consequences of climate change because of its long coastline and its climate region located in the tropics.

In general, climate change increases extreme weather events, strongly impacting people and ecosystems, especially vulnerable components. The challenge for building designers is how to mitigate impacts while cutting greenhouse gas emissions from the construction and operation of buildings. Facing such an urgent situation, studying on the impact of climate change on construction projects is an extremely necessary and appropriate content in the current context. The research has two basic goals to achieve as follows:

- How to assess the impact of climate change on projects: Develop indicators to evaluate future projects under climate change conditions.

- Impact assessment: Consider whether current design solutions help the building withstand and adapt to climate change and look for building design solutions that help the building best adapt to changes of climate.

The research target of the study is commercial buildings because this group of construction types is currently experiencing rapid growth in recent times in Vietnam, both in quantity and proportion of energy consumption and the generation of greenhouse gas emissions in buildings [1].

2. Literature review on climate change studies

In Vietnam, research on the impacts of climate change mainly takes place in the fields of agriculture, irrigation and human life. Scientific research on buildings under climate change conditions is very limited. In 2013, the book "Coping with climate change in industrial, urban and construction activities" was published [2], in which chapter 4 is dedicated to "Coping with climate change in architectural and construction activities". In 2015, we had an initial study on climate change, biological comfort and energy consumption - the challenges of design in the 21st century [3], and this can be considered one of the initial steps of the topic of climate change impacts on buildings in Vietnam.

The world's first publication on climate change and its impacts on building projects probably began in 1994 [4]. The most frequently cited report in this field is probably climate change and the indoor environment: impacts and adaptation [5]. Although limited to the UK, it covers a wide range of building types: 19th-century houses, new-build houses, 1960s flats, new-build flats, offices... For houses, Gaterell and McEvoy [6] present a study of the impact of climate change on existing detached housing developments in the UK, while Hacker et al. [7] include semi-detached houses. Wang et al. [8] focused on a residential facility building and various energy-saving variations in Australia, while Chan [9] presented the case for Hong Kong. In the office sector, Radhi [10] conducted a study on the impact of climate change on air-conditioned building projects in the United Arab Emirates, while Wan et al. [11] covered including air-conditioned offices in China; Chan [9] presents the situation in Hong Kong. Crawley [12] studied the impact of climate change on a small office building, at 25 locations worldwide covered by his climate data collection. The general conclusion of this study is that the impact of climate change will lead to a reduction in energy use of about 10% for buildings in cold climates, an increase in energy use of up to 20% for buildings in tropics climates and switch from heating to cooling energy in temperate climates.

Regarding the future increase in energy consumption due to climate change, Wan et al. [11] conducted a study of Hong Kong offices in a subtropical climate; The results show that office buildings have a 6.6% increase in total energy consumption during the period 2091-2100 when climate change scenarios B1 are applied (similar to the RCP4.5 scenario in [13]). Dirks et al. [14] investigated the impact of climate change on buildings in different climate zones of the United States. They demonstrated that in the hot, humid climate of Florida, office buildings would see a 15.2% increase in total energy consumption, while cold and temperate climates could see a decrease. Another study by Zheng and Weng [15] showed an average annual increase in building energy demand of 7.9% under the A1F1 climate scenario in 2050 for Los Angeles County. The above-mentioned studies have reported increased energy levels due to climate change, which are comparable standards for the results of this study.

3. Research methods

3.1. Select climate change scenarios

Predicting future global climate change is a difficult task and clear uncertainties always exist [13]. This study decided to use the high emission scenario RCP8.5 to evaluate the hypothetical impact of severe climate change on buildings. The climate change impacts of RCP4.5 and 6.0 are quite similar in the short term (i.e. 2046-2065) with a slightly larger impact of RCP4.5. However, in the long term (i.e. 2081-2100) RCP4.5 has a slightly smaller climate change impact than RCP6.0 due to the impact of climate policies. This study decided to choose the RCP4.5 scenario to represent the two intermediate scenarios of AR5. This study chooses the AR5 emission scenario because according to the "2020 Climate Change Scenarios" of the Ministry of Natural Resources and Environment of Vietnam, RCP (AR5) emission scenarios are built to estimate the following scenarios: Climate change until the end of the 21st century, along with roadmaps for publishing IPCC reports on global climate change. The RCP4.5 and 8.5 scenarios have also been applied in previous studies by Bilardo et al. [16] and Spandagos and Ng [17]. This choice is also completely compatible with Vietnam - Report of the Ministry of Natural Resources and Environment of Vietnam in 2016 [18].

3.2. Select time frames for future climate forecasts

A climate model is typically designed to predict future climate at different time frames. In this study, the projected years from 2020 to 2099 are divided into three time periods, called short-term (2026-2045), medium-term (2056-2075) and long-term (2080-2099), similar to the approach used in previous studies on climate change [19, 20]. Such a time frame division is also consistent with the IPCC's existing reports on climate change - AR4, AR5 - as well as the calculation models of the GCMs. This analysis only considers medium and long-term changes and impacts as short-term impacts appear to be predictable at this time.

Climate data files for the period 1961-1996 (Hanoi) and 1961-2017 (Da Nang and Ho Chi Minh City) are used as baseline climate data, representing “current” climate conditions. It is obtained from the ASHRAE IWEC database in TMY2 format. The period 1961-1990 is often used as a reference period in climate change studies and observations because weather data for this period is available for many study sites and has been completely validated, although it does not completely cover recent climatic conditions.

3.3. Select a model to calculate and predict climate change

The IPCC has approved and recommended several climate models (General Circulation Model - GCM), which is a mathematical model of the interactions between and within the ocean, land, ice and atmosphere [20]. For a given emissions scenario, there is still uncertainty about how the future climate will develop due to model limitations and the unstable nature of the climate system, so each model figure brings a significant difference. For this reason, we need to rely on the average of several GCMs, rather than on a single prediction of one GCM, to see the range of possible climate forecasts given by the GCMs that can occur.

WeatherShift software tool® [21] by Arup and Argos Analytics LCC was able to meet this challenge as it combines 14 GCMs among the recently published GCMs, for two emission scenarios, RCP4.5 and RCP8.5. The criteria for selecting the 14 GCM models were resolution scale, predictor variables, and generation in the RCP8.5 and 4.5 emission scenarios. This tool will arrange the forecast results of each GCM into a cumulative distribution function (see section 14 GCM in reference [22]) with specific percentage ranges: 5%, 10%, 25 %, 50%, 75%, 90%, and 95%. From this cumulative distribution function, changes in temperature, humidity, radiation... are predicted according to the above mentioned percentage levels. A forecast value of around 50% is an "average" value, smoothing out the uncertainty between GCMs and stochastic climate variations (refer to Figure 1 to see how the cumulative distribution function works in WeatherShift®).

In the WeatherShift program®, future weather data sets produced by GCMs are downscaled (increased in spatial resolution - detailed to a smaller geographic area - and temporal - detailed to separating days or hours) to meet the requirements of most building energy simulation software using the "morphing method" of Belcher et al. [23].

Additionally, several other weather tools can increase resolution and generate future weather files based on GCM forecasts. Examples are CCWorldWeatherGen tools, Meteonorm 7.3, WeatherGen (available at: http://139.62.210.131/weatherGen/), but they only support old climate change scenarios from 2007. None of them support climate change scenarios under RCP4.5 and 8.5 scenarios, so they were not selected.

In this study, weather data in "epw" format for the EnergyPlus simulation program were generated by the WeatherShift tool®, with 10%, 50% and 95% levels of the cumulative distribution function of the 14 GCMs included in WeatherShift®.

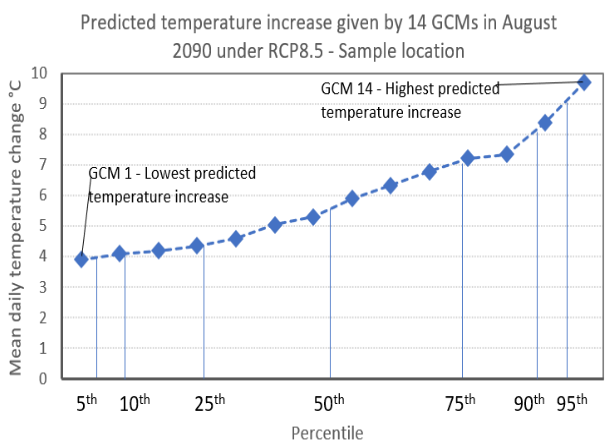


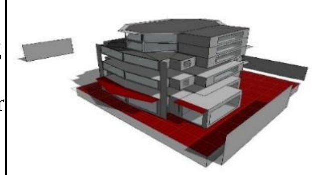
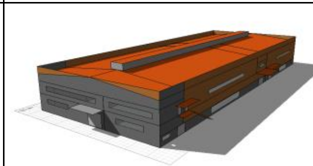
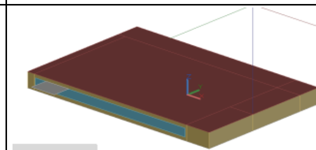
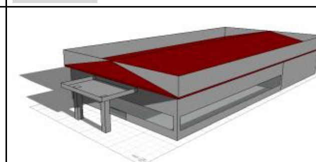
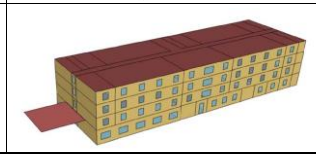
Figure 1. *Cumulative distribution function of 14 GCM forecasts and percentage intervals available in the Weathershift® tool (adapted from Weathershift®)*

This study uses simulation modeling to analyze the energy consumption and emission levels of commercial buildings. The software used for simulation in this study is EnergyPlus version 8.8.0 developed by the US Department of Energy. This is the most widely used software in building energy simulation research today. Representative commercial buildings for each type have been identified as shown in Table 1.

3.4. Building performance indicators and how to evaluate them

Most studies evaluating building performance under the impact of climate change use a single indicator, usually energy level for heating, energy level for cooling or overheating time. In this study, two indicators of carbon emission level and average overheating time are used. This study considers the first indicator as the main indicator, while the second indicator is a binding indicator or a secondary indicator (if the two projects have similar main indicators).

Table 1. *Preliminary information of representative commercial projects for research*

	Building type	Base building model	Energy model
1	Office	Office building in Hanoi, Plaschem tower (17 floors)	
2	Factory – warehouse	Nippon Rika Vietnam Co., Ltd. Factory	
3	Retail	Mega Market in Da Nang	
4	Restaurant	White Palace Restaurant in Ho Chi Minh City	
5	Hotel	Hotel block in Hai Tien resort	

4. Result

4.1. The impacts of climate change on energy consumption and total greenhouse gas emissions of the project

Obviously, with the increase in temperature under climate change conditions, buildings are forecast to increase energy consumption for cooling to ensure biological comfort in the building. Accordingly, projects will increase greenhouse gas emissions, and as a result, the greenhouse effect causing global warming will become even more serious. In this section, the study synthesizes data and compares emission levels and overheating time levels in a base model of 5 representative commercial buildings under different climate change scenarios. Figure 2 shows the carbon emission increases of the baseline model under climate change conditions. All types of commercial buildings considered here have increased carbon emissions. The increase corresponding to the long-term RCP 4.5 climate change scenario is from 6% ≈ 12%. Meanwhile, the increase corresponding to the long-term RCP 8.5 climate change scenario is from 12.6% ≈ 22%. Restaurants and hotels are the types of commercial buildings with the most significant increases in emissions.

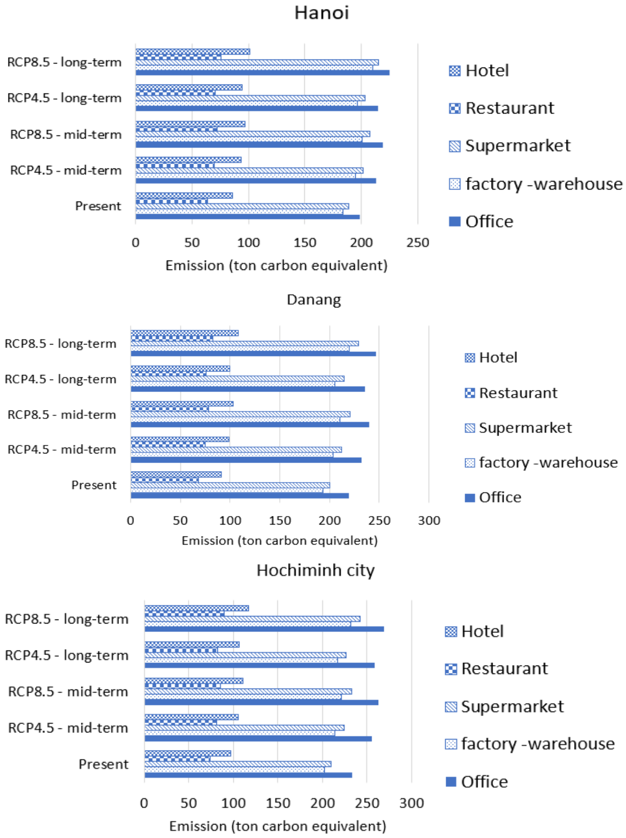


Figure 2. *Summary of carbon emissions levels of commercial buildings by region*

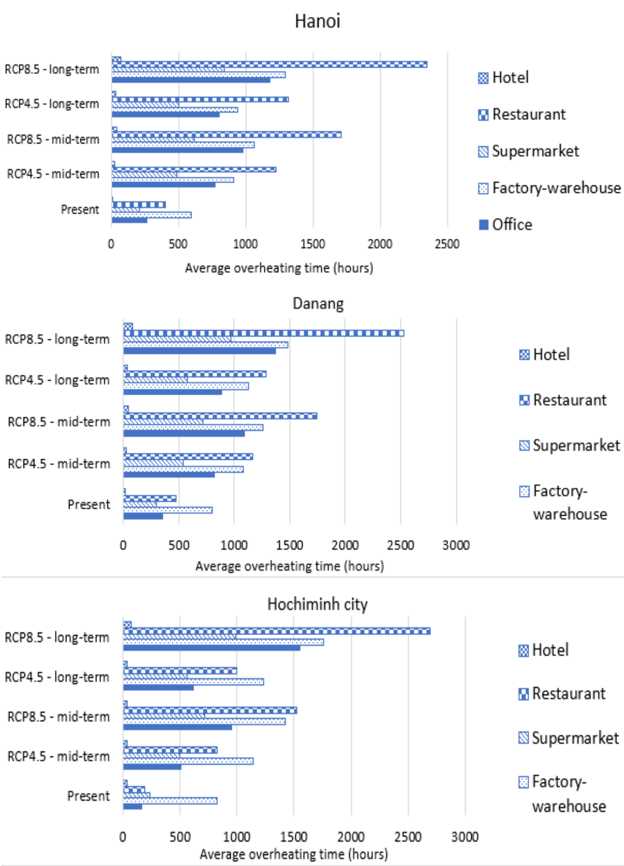


Figure 3. *Average annual overheating time of commercial buildings by region*

Compared to the increase in energy consumption in other countries with similar climates, we see a good correlation. Accordingly, office buildings have increased by about 15.2% in Florida, USA (with all the climate types of 3 cities in Vietnam) by 2089 [14]. Meanwhile, according to Wan et al. [11] in Hong Kong - with a subtropical climate - office buildings will increase by 6.6% between 2091-2100 if climate change scenario B1 (equivalent to with RCP4.5 scenario). Another study [24] shows a 7.9% increase (medium-sized office buildings) under scenario A1F1 (similar to RCP8.5) by 2050 for the Los Angeles county region. The relatively consistent results above allow us to confirm the reliable emission increase of this study.

Not only does it increase carbon emissions, but climate change also increases thermal discomfort in buildings. Figure 3 compares the increase in average overheating time in the baseline model of commercial buildings under climate change scenarios. It can be seen that climate change will overload the building's active cooling system, causing the overheating time in the building to seriously increase. Even though it took more energy to make the cooling system work harder, the overheating time still increased.

4.2. Find solutions to minimize greenhouse gas emissions under future climate change conditions

Passive design and operation solutions were chosen in this study because they can be completely decided and controlled by the building designer as well as the building users, relying almost exclusively on rules of natural movements (wind, solar radiation, temperature, humidity...). The optimization results and operational design solutions of the optimal model are studied through simulation-based optimization techniques.

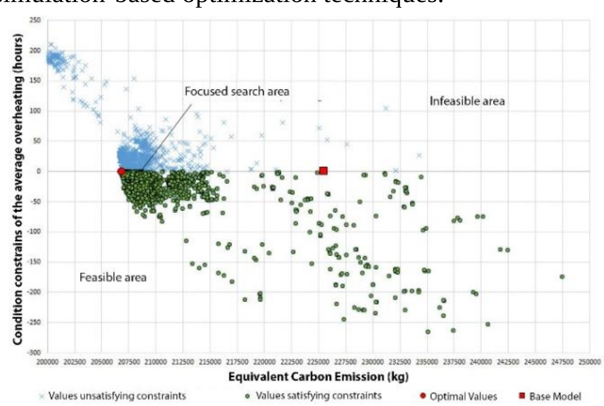


Figure 4. *Graph showing the objective function values through the constraint condition of the overheating hours, building type: office, RCP8.5, 2080-2099, Hanoi*

Figure 4 shows the office optimization process under climate change conditions in Hanoi. Values of the objective function that do not satisfy the constraints (solutions with an X sign) are eliminated. The optimal value location is the smallest extremum found after a continuous search focusing on the area where the carbon equivalent emission value is about 200 tons of carbon and the average number of overheating hours is less than the baseline model -1 hour. The optimal solution for offices in Hanoi reveals that:

- First of all, the best building orientation angle is the rotation angle of 72.30 from true North clockwise.

- The insulation layer of the outside wall requires a maximum of 5 cm, the thickness of the roof insulation layer is 1.87 cm, the insulation level is quite low compared to the allowable level. The project is required to paint the exterior walls and roof with bright white, in this study optimal results for both exterior walls and roof have a value of 0.25 (solar absorptance).

- For building glazing facade, the lower the SHGC coefficient, the less solar radiation enters the building, making the building cooler and reducing the cost of electricity consumed for cooling needs. The optimal value for the SHGC coefficient is 0.3, the building's facade is double-layered glass with an Argon air layer with a thickness of 2 cm.

- Sunshades on windows should extend about 0.8 m, and adding horizontal louvers outside the building will make the building better reduce the absorption of solar radiation.

- The building should be ventilated throughout the year at night, the building should be ventilated to change ½ of the entire air layer per hour with an ACH factor of 0.5 times/hour. A wall thickness of 200 mm should be maintained indoors as a thermal mass to help maintain temperature stability in the building. Reinforced concrete floor thickness should reach a value of 20 cm.

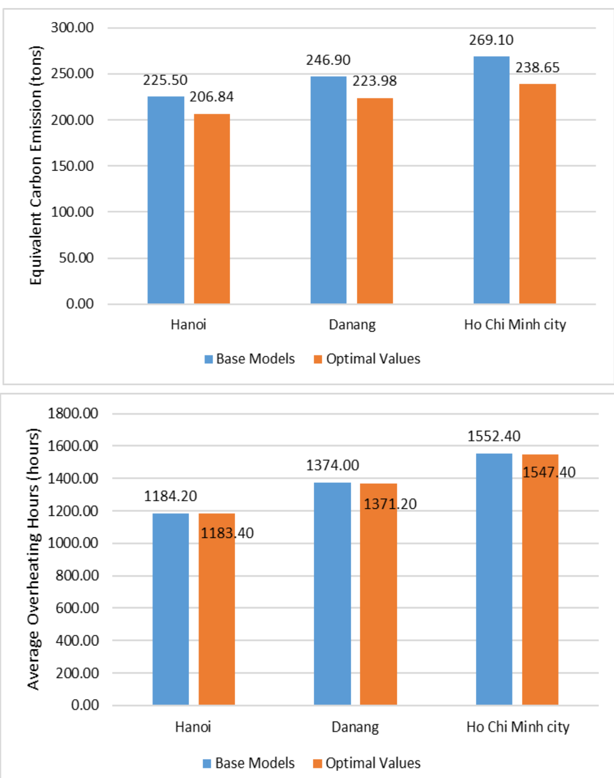


Figure 5. *Carbon emission optimization value chart and average overheating hours, Office, RCP8.5, 2080-2099*

The above-mentioned optimization results help designers to specifically determine the appropriate passive design strategy for each locality while still ensuring good thermal comfort inside the building.

4.3. Overall average reduction for severe and less severe climate change scenarios

Through calculating the data obtained from 240 simulations of the performance of the baseline model and the optimal model under more severe and less severe climate change scenarios than forecast, we can derive the effectiveness of the optimized model compared to the base model as shown in Table 2. The results show that in the southern climate region, which is warmer, the efficiency of the optimal model is always higher than in the north. The average carbon emission reduction ranges from 10.0% to 14.2%. The average reduction in overheating hours ranges from 14.5% to 28.7%.

Table 2. *Emission reduction efficiency and average number of overheating hours if climate change is more severe than average (95%) and less severe than average (10%)*

	Harsh climate change (95%)		Climate change is less severe (10%)	
	Average emissions (%)	Average number of overheating hours (%)	Average emissions (%)	Average number of overheating hours (%)
Hanoi	11.0	14.5	10.0	19.8
Da Nang	12.9	20.9	11.7	27.2
Ho Chi Minh City	14.2	25.9	13.1	28.7

Thus, only with passive design solutions and building envelope solutions can designers help commercial buildings significantly reduce emissions in the future and building performance gains higher stability.

Due to the limited volume of the article, details about climate change scenarios, how to conduct simulation and optimization along with a summary of design solutions to adapt to climate change in the period 2050- 2080 for each type of project, corresponding to each climate zone were fully introduce it via www at:

A guide to climate-resilient architectural design is available at: https://dut.udn.vn/KhoaKientruc/Tintuc/id/7018

In this guidebook, we introduce climate change adaptation design requirements, along with the requirements of the Vietnamese Code on Energy Efficient Building Design QCVN 09/2017. Users can compare to see the higher requirements compared to the codes in this guidebook.

5. Conclusion

Climate change has had a strong impact on all aspects of human life and on building projects. The study used forecasting models based on climate change scenarios RCP 4.5 and RCP 8.5 along with appropriate downscale tools to forecast the climate of regions in Vietnam. By using energy and building simulation methods combined with simulation-based optimization techniques, we have assessed the impact of climate change on commercial buildings in Vietnam in the medium and long term. The results show that under the impact of climate change, the carbon emissions of commercial buildings in Vietnam would increase corresponding to the long-term RCP 4.5 climate change scenario, from 6% ≈ 12%; the long-term RCP 8.5 scenario from 12.6% ≈ 22%. Depending on the scenarios, the average overheating time inside buildings can increase many times. Not only that, climate change also causes building microclimate control systems to be overloaded and unable to ensure microclimate conditions inside the buildings. From the optimization results, we also derive commercial design solutions to adapt to climate change in the medium and long term for the main localities in Vietnam: Hanoi, Da Nang and Ho Chi Minh City.

From the optimization results, we also derive commercial design solutions to adapt to climate change in the medium and long term for the main localities in Vietnam: Hanoi, Da Nang and Ho Chi Minh City. A handbook on architectural design solutions for commercial buildings adapted to climate change in the period 2050 - 2100 was also built for application purposes. The handbook is an essential reference for building designers, helping them easily choose appropriate design solutions to reduce greenhouse gas emissions and meet regional and national goals.

This is an interdisciplinary scientific study with wide coverage of subjects, space and time, so it is inevitable that there will be limitations or opportunities to improve future research. Although they are the best forecast results under current scientific and technological conditions, climate change scenarios have a very large degree of uncertainty because they depend heavily on socio-economic factors. For example, the scenarios RCPs do not anticipate that the Covid-19 epidemic will significantly reduce global emissions in 2020 and 2021 compared to normal situation, whether this affects the forecast results of climate change still being a big question mark. In addition, due to limited time and resources, we have not been able to evaluate how the design solutions adapted to climate change to reduce emissions that we discovered above are different from other design solutions relying on personal experience and does not take into account the issue of climate change. Finally, a small limitation comes from the optimization method itself. In a large and discontinuous search space, no search algorithm can reliably guarantee that the most optimal solution will be found. In case it is not found, the solution found is at least a near-optimal solution. It provides superior performance compared to buildings that have not been designed to reduce emissions.

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