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Multi-phase framework for optimization of thermal and daylight performance of residential buildings based on the combination of ventilation and window design

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ABSTRACT
The environmental design of residential buildings is an arduous process involving a large number of parameters and objectives. Additionally, with the development trend of high-performance housing around the world, its disadvantage – the risk of overheating – has begun to increase, which further shows the importance of comprehensive optimization of residential buildings. This study presents a highly optimized target framework for residential buildings based on the adjustment of window-related parameters coupled with various natural ventilation patterns. Multiple phases are carried out in this optimization framework to optimize three objectives, i.e., energy consumption, thermal comfort, and daylight environment simultaneously. Phase 1 applies various natural ventilation patterns to explore the improvement potential of ventilation patterns. Phase 2 implements a genetic algorithm to achieve the Pareto optimization of window-related parameters. Phase 3 filters more robust Pareto-optimal solution based on Multi-Criteria Decision-Making logic to meet the different needs of different skateboards and architectures. The innovation and scientific significance lie in parameters include both the building envelope elements and ventilation patterns, as well as highly targeted for residential buildings. The results show that natural ventilation effectively improves the potential for simultaneous optimization of multiple objectives, and the optimization framework can adapt to residential buildings with various envelope insulation performance.

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1. Introduction

1.1. Background

Since the first industrial revolution, global energy consumption has been increasing rapidly due to the increase in the number of vehicles, the development of industrialization, and the emission of enormous amount of greenhouse gas (Wongtanachai et al. 2012). In 2016, energy consumption of buildings account for approximately 30%, nearly 125EJ, of global energy consumption; wherein 28%, nearly 91.7EJ, of carbon dioxide emissions comes from residential. Residential buildings cause about 17% of global energy-related carbon dioxide emissions directly and indirectly (Dean et al. 2016). As a consequence, building high energy-efficient residential buildings, Zero-Energy Houses (ZEH) or nearly Zero-Energy Houses (nZEH), has become the main task for modern urbanization and sustainable social development around the world.

In recent years, a large amount of passive design strategies and a variety of policy activities emerged to build high-performance residential building. In Japan, more than half the residential buildings newly built by 2020 are expected to be ZEH (Efficiency and Division 2015), and Energy performance of buildings directive (EPBD) also clarified that by 31 December 2020, all new buildings, including residential building and non-residential building, within EU will be Zero-Energy Buildings (Hemerlink Andreas et al. 2013). Consequently, the number of residential buildings with high thermal insulation and high air tightness has increased rapidly following market demand. However, some Post-Occupational Evaluations (POE) on nZEBs indicated that occupants generally feel higher levels of thermal comfort in winter than off-heating season, especially in summer (Mlecnik et al. 2012). This is mainly results from inappropriate or excessive insulation property and air tightness for building envelope (Fabbri and Tronchin 2015; Duran, Taylor, and Lomas 2015), inappropriate or inadequate consideration or selection of multiple passive strategies (Duran, Taylor, and Lomas 2015; Derbez et al. 2014), and poor design for natural ventilation application (Tuwii et al. 2017). Hence the risk of overheating in these high insulated houses has become one of the most important problem around world (Dodoo and Gustavsson 2016; Gupta and Gregg 2018; McLeod, Hopfe, and Kwan 2013; Mlakar and Štrancar 2011). Overheating causes thermal discomfort on occupants and even affect occupants’ health, such as heart attack, stroke, or sudden infant death (Hughes and Natarajan 2019; Perinatal Services BC). In addition, overheating also significantly results in unexpected energy consumption and discomfort during the summer and transition season.

1.2. Literature review

Researchers all over the world have conducted studies extensively to focus on improving nature ventilation, the most effective passive cooling strategy, for easing overheating or reducing unexpected cooling load. Liu and Lee (2019) showed indoor ventilation performance of units residential in Hong Kong, quantified by air change rate, is most sensitive to variation of wind condition followed by ventilation mode window type and window orientation by site measurement and simulation of Computational Fluid Dynamics, and optimization results indicated that appropriate window type even double ACH. T van Hooff et al. (2016) coupled several passive climate change adaption measures by dynamic thermal simulation using EnergyPlus to verify that carefully combination of appropriate natural ventilation with other passive measures can significantly reduce cooling energy for a typical Dutch terraced house. Sorgato, Melo, and Lamberts (2016) showed that the occupant behavior in relation to the operation of natural ventilation dramatically affects annual load and thermal comfort of single-family residential buildings in humid subtropical climate. S.M. Porritt et al. (2012) conducted a series of dynamic thermal simulations to evaluate the influence of three interventions, insulation, and solar control as well as natural ventilation, on annual space heating load use and overheating reduction of solid wall terraced housing of UK. The result indicated that controlling natural ventilation during hottest part of day is effective for elderly occupants, and night ventilation is beneficial to cooling load and overheating reduction.

These studies mainly focus on improving thermal performance during off-heating season by adjusting various parameters of building or occupant to improve use of natural ventilation. Nevertheless, building environmental design is a complex process that can be defined as a multi-objective optimization problem. Individual parameter needs to be adjusted to take into the impact on various objectives. Window is one of the most influential elements of building envelope that needs to be considered as multi-objective optimization problem. For example, window can substantially affect energy consumption, thermal comfort, visual comfort, and various parameters directly and indirectly. Yingni Zhai et al. (2019) proposed a method combines Non-dominated-and-crowding Sorting Genetic Algorithm II (NSGA-II) with EnergyPlus to optimize a variety of window parameters which included WWR, orientations, thermal insulation property of multi-layers glass. This method generated a series of optimal or near-optimal solutions that effectively optimize energy consumption, thermal environment, and visual performance of a room of office simultaneously.
Salata et al. (2017) examined the potential of optimizing primary energy consumption versus investment cost of residential building with different thermal insulation properties of glass surfaces and frames combined with other interventions within designated constraint by genetic algorithm to find suitable solutions consist of the several interventions. Facundo Bre et al. (2016) presented optimization methodology combined with sensitivity analysis considering energy and thermal performance of single-family house. The sensitivity analysis indicated the type of external wall and the window variables related to window infiltration rate are the most influential design variables on the mentioned objective functions and on the basis of sensitivity analysis the methodology makes a dramatically improvement of the considered house.

Numerous researchers have demonstrated the significance of natural ventilation to high-performance building in the context of climate change by various ventilation-related studies. In the meantime, the quantity of studies focuses on the development of optimization methodology to predict the improvement environmental requirements and find optimal solutions of various types of building by sorting out the correlation between various building interventions and multiple objectives are also on the rise in recent decades (Ekici et al. 2019). However, few studies highly targeted explore the optimization potential of various objectives and find nearly optimal solutions of high-performance residential buildings through an in-depth exploration of the synergy between window-related parameters with various natural ventilation patterns.

1.3. Research purpose

This paper aims to study the risk of overheating in high-insulation performance residential buildings located in the temperate zone and proposes a multi-phase optimization framework that combines various survey-based natural ventilation patterns and adjustment of window-related parameters to reduce annual energy consumption while improving indoor environmental quality (IEA), i.e. thermal comfort and indoor daylight environment.

In addition, the scientific contribution of this study is to show in detail the impact of overheating on the energy consumption and thermal comfort of residential buildings with different envelope performance through multiple case studies, and then demonstrate the applicable scenarios of various alternative natural ventilation methods to solve the problem of overheating. Through the combination with multi-objective optimization framework, it is proved that different ventilation methods can improve the optimization upper limit of thermal environment (i.e. energy consumption and thermal comfort) and even lighting environment of residential buildings with different performances, it also effectively mitigates the conflict between the simultaneous optimization of the thermal environment and the light environment during window adjustment. This study provides a reference for the future study of residential building ventilation when considering multiple physical environments.

Optimization framework developed by this study is described in Section 2 followed by the details of case in Section 3. Results of the dynamic thermal simulations and optimization are discussed in Section 4. Section 5 concludes and discusses the future work.

2. Framework of optimization method

2.1. Simulation tools

In this study, the geometry of calculation model is created by 3D graphic software Rhinoceros (Rhinoceros), its plug-in Grasshopper (Grasshopper) constructs the decision variables of the whole optimization workflow. Honeybee and Ladybug (Honeybee and Ladybug) are applied to add thermal insulation properties such as defining each zone inputting detailed internal heat gain and inputting the calculation model information. These data are calculated with the thermal simulation engine Energyplus (Energyplus) and daylight simulation engine Radiance (Radiance). Lastly, Octopus (Octopus) as a multi-objective evolutionary optimization plug-in is applied to screen the simulation results and automatically iterate the simulations.

2.2. Overview of framework

A multi-phase and multi-objective optimization framework was developed by this study which considers various natural ventilation patterns and window-related parameters as factors. Three phases involved in this optimization framework are detailed in the following subsections (Figure 1):

- Phase 1: In the case of building interventions unchanged, various natural ventilation patterns produced by combination of logic-based nocturnal ventilation and survey-based daytime ventilation are applied to the mModel. The effect of each ventilation patterns is showed through the comparison with the unventilated state to find the ventilation pattern with greatest improvement potential.
• Phase 2: A genetic algorithm (GA) is implemented to achieve the multi-objective optimization process of minimizing energy consumption, improving thermal comfort and visual comfort by adjusting the window-related intervention of the simulation model with the ventilation pattern selected in Phase 1.

• Phase 3: Aiming to take account of needs of different decision-makers, a system of evaluation and proposal for optimal or near-optimal solutions produced in Phase 2 is proposed based on multiple choosing criteria, i.e. Load & Daylight preferred, Load & Comfort preferred, Comfort & Daylight preferred.

2.3. Natural ventilation pattern

In this study, two periods of natural ventilation were proposed during a day according to the occupancy schedule of Japanese, daytime ventilation from 6 am to 9 pm, i.e. the waking hours and nocturnal ventilation from 9 pm to 6 am, i.e. shower and sleep hours. Since the windows are sliding windows, when the windows stay in the “on” state, the effective ventilation area is set to 50% of the total area of the window. Daytime ventilation was developed by a window operation logic counting indoor temperature, ambient absolute humidity, rainfall, outdoor wind speed, namely, only when the above four environmental conditions meet the state shown in Figure 2 can daytime ventilation be performed. The indoor temperature is simulated by the simulation engine shown in Section 2.1, and other three judgment conditions come from weather data. As to nighttime, for the reason that occupants are mainly asleep, the windows are hardly influenced by the above-mentioned logic. Therefore, the logic of nocturnal ventilation was developed based on local weather conditions assuming that windows always on or off from 9 pm to 6 am.

Figure 1. Flow chart of optimization framework.
Through the combination of nocturnal ventilation and daytime ventilation, three characteristic natural ventilation patterns are determined and applied to this study (Figure 3). Ventilation volume of pattern ① betwixt that of pattern ② and ③, well balance the effect of ventilation on energy consumption and thermal comfort; pattern ② gives rise to relatively small amount of ventilation which avoids the indoor temperature is too low results from nocturnal ventilation during transition season but the improvement effect for cooling load and thermal comfort in summer is not as good as the other two pattern; pattern ③ brings massive ventilation volume which greatly reduces cooling load and ease overheating but with risk of discomfort caused by low temperature during transition season and slightly increases heating load. On account of these three ventilation patterns have a large span of ventilation time from low to high, which helps to better explore the range of ventilation improvement potential. In addition, on the basis of site-measured data, the air changes per hour (ACH) in this study are set as five times per hour.

2.4. Objective functions

The objective functions used in the optimization framework proposed in this study are described in detail in this part, include usage motivation and physical characteristics of application, as well as the simulation engine and calculation method used to simulate each physical environment.

For a start, annual energy consumption and thermal comfort under the state of free-running and air conditioned are included in the objective of this optimization method, and the simulation engine both of these two evaluation indicators are Energyplus. Meanwhile, part of passive strategies improves energy and thermal comfort performance by sacrificing daylight environment, one of the most important environmental factors in residential buildings (Li et al. 2006), such as mounting shading devices, lowering WWR, etc. And the daylight use also associates with the utilization of solar radiation, which serves as the most significant means to reduce cooling load and improve physical and psychological thermal

**Figure 2.** Flow chart for judgment of daytime ventilation.

**Figure 3.** Three natural ventilation patterns.
comfort in winter. Consequently, on account of the snowy and cold climate characteristics in winter of case study location, daylight utilization performs as one of the optimization objectives in this study. The simulation engine of daylight environment is Radiance.

Various indices have been proposed to assess the aforementioned three aspects. However, the different indices evaluate one specified aspect differ from each other for various features, i.e. space discretization, time discretization, acceptability criterion mainly for comfort (Carlucci et al. 2015). Considering non-sedentary state of occupants in residential buildings as well as high computation cost and a huge amount of calculation of GA-based optimization, the indices of three aspects characterized by following subsections are selected to construct the objective-functions:

- Index with single value aggregates all simulation values for each point over the map inside space.
- Index with single value aggregates all simulation values for each time point over a period.
- Index, mainly for comfort, with one threshold to calculate the acceptable time ratio.

The ultimate goal of using genetic algorithm–SPEA (De Dear Richard 2004) in this study is to maximize the thermal comfort and lighting comfort while minimizing the annual load. Due to the GA deals with the simultaneous optimization of multiple objectives, and there is a trade-off relationship between each goal, this optimization framework did not aim to seek an optimal solutions for a single objective but to produce a set of near optimal solutions by comprehensively considering multiple objectives. These near optimal solutions have their own strengths, that is, they will have excellent performance in certain specific objective areas, while ensuring a relatively good overall performance in all objective areas. This form of optimal results not only ensures that the building has good environmental performance, but also provides a flexible decision-making space for designers to make decisions based on design elements.

### 2.4.1. Objective function for energy consumption

The annual load is calculated with a cooling setpoint of 27°C in summer, a heating setpoint of 20°C in winter, non-air-conditioned during transition season, and the air conditioner is set to run 24 hours a day. The objective function for energy consumption is defined as the calculation of annual load. In addition, the weather file of Kurobe, Japan used in this study is described in detail in Section 3.7 combined with case study.

#### 2.4.2. Objective function for thermal comfort

There are two broad categories of assessment index aim to evaluate the thermal comfort of free-running state and air-conditioned state of building, the adaptive approach, and rational approach. Adaptive approach based on a series of field studies verifying the relevance of acceptability of thermal environment and ambient under the non-sedentary state of humans in unsteady-state conditions and predicts thermal comfort of humans with behavior adaptation, physiological adaptation, and psychological adaptation (De Dear Richard 2004). And rational approach predicts thermal comfort of human remains near-stable personal clothing insulation, activity level, and involved in steady-state conditions, best represented by the Fanger comfort model (Fanger 1970).

In consideration of high autonomy and controllability of the residents to the air condition, the non-air-conditioned time ratio during transition season even summer and winter in residential building is unpredictable and usually higher than other types of building. Therefore, besides commonly assessed thermal comfort in air-conditioned state, the thermal comfort of free-running state also acts as a crucial role in evaluating the thermal performance of residential buildings.

To avoid the effect of unpredictable air condition operation schedule of residents to simulation accuracy, the free-running state period is set not only during transition season but also winter (heating season) and summer (cooling season). The air-conditioned state period is summer and winter, air conditioner was set to run 24 hours a day. Consequently, the optimization framework proposed in this paper capable of improving the thermal comfort at any time of a year in these two states simultaneously without the interference from HVAC operation schedule. And two objective functions evaluating comfort of these two states are constructed based on the indices belonging to adaptive approach and rational approach.

**2.4.2.1. Thermal comfort of free-running state.** The Adaptive Thermal Comfort (ATC) model of ASHRAE 55–2010 (A.S. ASHRAE, Standard 55-2010 2010) is used in this study to evaluate the annual thermal comfort of free-running state that defines the acceptable zone of occupants in free-running building based on the relationship between indoor comfort temperature and outdoor average temperature in the format of Equation (1): \[ T_{co} = 17.8 + T_{ref} \times 0.31 \] (1)

Where \( T_{co} \) = indoor comfort temperature and \( T_{ref} \) = prevailing mean outdoor temperature. Moreover, two bandwidths derive from Equation (1) to represent 80%
2.4.2.2. Thermal comfort of air-conditioned state.

In view of the high glazing ratio of objective model, radiant heat and loss through the window dramatically affect occupants’ actual experiences to thermal environment. Window size and the insulation level of window are the only building decision variables in this study, the variation of these two factors prone to resulting in radiant asymmetry especially in conditioned building, due to the stable indoor air temperature controlled by HVAC system. Consequently, operative temperature, the index highlights the effect of radiant to thermal comfort, was used in this study to evaluate the thermal comfort of air-conditioned state calculated by Equation (2) according to ASHRAE 55–2010 (A.S. ASHRAE, Standard 55-2010 2010):

$$ T_o = \frac{(T_a + T_r)}{2} \tag{2} $$

Where $T_o$ = operative temperature, $T_a$ = air temperature, and $T_r$ = mean radiant temperature. Moreover, in accordance with 2009 ASHRAE Handbook-Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2009), all surfaces of the objective model are assumed to be the black, so that the mean radiant temperature is calculated by Equation (3)

$$ T_r = T_1^4 F_{P-1} + T_2^4 F_{P-2} + T_3^4 F_{P-3} + \ldots + T_N^4 F_{P-N} \tag{3} $$

Where $T_r^4$ = mean radiant temperature, $T_N = $ surface temperature of surface N, and $F_{P-N}$ = angle factor between a person and surface N.

In addition, the objective function of thermal comfort in air-conditioned state is constructed by averaging thermal comfort time ration (Equation (4)) of all measurement points which locate on the test surface 0.6 meters above the ground, the height of 0.6 meter represents the waist-height of a sitting person recommended by ASHRAE 55–2010 (A.S. ASHRAE, Standard 55-2010 2010), and measurement point is set every 0.5 m² to ensure the accuracy as well as reduce the calculation cost. Radiant thermal comfort time ration = number of hours that operation temperature within comfort zone/The total hours of air-conditioned period (4)

The comfort zone of operation temperature is set according to the ISO 7730 (2005) from 23 to 26°C in cooling season and 20 to 24°C in heating season. The clothing insulation is assumed to be 0.5 clo in cooling season and 1.0 clo in heating season, the metabolic rate is 1.2 met throughout the year. Furthermore, based on the characteristic that octopus only solves the optimization problem with minimizing trend, the displayed value of this objective function is also designated as 1 minus comfort time ratio. The whole process is as shown in Figure 6.

![Figure 4. Comfort bandwidths of adaptive thermal comfort.](image)

and 90% occupant acceptability ranges (Figure 4). In this study, the bandwidth of 80% is used to define the lower and upper limit of the comfort zone.

In addition, on account of the limitation that the equation only works when outdoor dry bulb temperature ranges from 10°C to 33.5°C, all temperatures below or above this range are calculated as their adjacent boundary temperatures.

The objective function of thermal comfort in free-running state is defined as the time ratio in the comfort zone of the natural room temperature ATC model at the center of the room throughout the year; furthermore, since the octopus only solves the optimization problem with minimizing trend, the value of the objective function is designated as 1 minus comfort time ratio (Figure 5).

![Figure 5. Flow chart of constructing thermal comfort objective function in free-running state.](image)

![Figure 6. Flow chart of constructing thermal comfort objective function in air-conditioned state.](image)
2.4.3. Objective function for indoor light environment

According to the European standard EN12665, visual comfort is defined as “a subjective condition of visual well-being induced by the visual environment” (SESKO Standardization in Finland 2003) and depends on the physiology of the human eye, the amount of light and distribution in space, and the spectral emission of artificial light sources. Because the residents are less constrained with the indoor space usage adaption to daylight can be achieved via moving in order to significantly reduce the risk of glare and the effect of uniformity of light. This study optimizes the indoor light environment by studying the amount of natural daylight driven into the room.

The Daylight Autonomy (DA), the first annual daylight metrics with the capability to show up the dynamic daylight environment, is widely used around the world. Instead of presenting through a map, IES proposed the spatial Daylight Autonomy (sDA), defined as the percentage of floor area that exceeds a specified illuminance (e.g. 300 lux) for a specified percentage of the analysis period (IESNAI, LM-83-12 IES Spatial Daylight Autonomy (sDA) and Annual SunlightExposure (ASE) 2012), to depict the dynamic daylight environment via a spatial value. For the characteristic above, the objective function for daylight usage is constructed based on sDA, with the assumption that occupancy period is between 7:00 am and 17:00 pm and an hour lunch break at 12:00 am throughout the year and set one sensor per 0.5 m² on the 0.7 m height plane of the whole model. The details of the Radiance parameters of sDA calculation are shown in Table 1. Based on the characteristic that octopus, the displayed value of the objective function is designated as 1 minus sDA.

2.5. Decision variables

For optimizing the energy consumption, thermal comfort and daylight environment in combination with natural ventilation, the building parameters highly related to these three objectives and ventilation were selected as decision variables, namely window properties (U-value, SHGC, and VT) and window size. And these two decision variables will be described in detail in Section 3.2 along with the description of case study model.

2.6. Selection logic of optimal results

This research uses a logic called Multi-Criteria Decision-Making (MCDM) to further filter more robust Pareto-optimal from the Pareto-front and meet the different needs of different skateboard and architectures:

- Step 1: Selected the Pareto optimal that values of all four objective functions are better than pre-optimization.
- Step 2: Ranked each of four objective functions values of all the Pareto optimal selected in Step 1 respectively to form four lists, i.e. the ranking list of energy consumption values, and ranking lists of thermal comfort values (time ration within the comfort zone of ATC and OT), and ranking list of sDA values.
- Step 3: Proposed three criteria (1) Load & Daylight preferred (2) Load & Comfort preferred (3) Comfort and Daylight preferred
- Step 4: Filter the more robust optimal solutions based on three criteria.
- Load & Daylight preferred: Select the optimal solutions of which the value of load and sDA both rank in the top 50% in their respective lists, then rank the value of thermal comfort of these optimal solutions and select the top three.

Table 1. Settings of the Radiance simulation parameters.

| Ambient bounces | Ambient division | Ambient sampling | Ambient accuracy | Ambient resolution | Direct threshold | Direct sampling |
|-----------------|------------------|------------------|------------------|-------------------|-----------------|----------------|
| 6               | 1500             | 100              | 0.1              | 300               | 0               | 0              |
Load & Comfort preferred: Select the optimal solutions of which the value of load and thermal comfort both rank in the top 50% in their respective lists, then rank the value of sDA of these optimal solutions and select the top three.

Comfort & Daylight preferred: Select the optimal solutions of which the value of thermal comfort and sDA both rank in the top 50% in their respective lists, then rank the value of load of these optimal solutions and select the top three.

3. Case study
As a case study, the optimization framework is applied to a single unit of an existing residential building located in Kurobe City, which is in the northeastern part of Toyama Prefecture, Japan.

3.1. Climate data
With bordering the Sea of Japan to the west and latitude of approximately 36.5°, the climate of Kurobe is characterized by cold and heavy snow in the winter, hot and humid in the summer, a typical rainy and snowy area of Japan. The average annual temperature is 13.7°C with the lowest and highest temperature occurs in January and August that are slightly below 0°C and around 31°C respectively (https://www.travel-zentech.jp/world/kion/Japan/Yatsuo.htm). Summer usually lasts from June to September. With outdoor temperature ranges between 25°C and 30°C for most of these four months, the rainfall is approximately 650 mm (https://www.travel-zentech.jp/world/kion/Japan/Temperature_in_Toyama_Prefecture.htm). The winter of Kurobe lasts about four months from December to March. The temperature is between 0 and 9°C with more than 50 snow days that leads to total snowfall of approximately 750 mm (https://www.travel-zentech.jp/world/kion/Japan/Temperature_in_Toyama_Prefecture.htm).

Long winter and remarkable snow result in the main passive strategy applied to the residential building in Kurobe is enhancing thermal insulation performance of envelope mainly for reducing space cooling load, which also results in overheating phenomenon or potential risk of overheating coupling with the relatively high temperature and humid climate characteristics of summer and ending of spring as well as starting of autumn.

Moreover, during summer, the diurnal outdoor temperature variation of Kurobe is between 5°C to 10°C and the nocturnal outdoor temperature is generally stable between 20°C to 23°C which is suitable for nocturnal ventilation. Therefore, nocturnal ventilation of Kurobe was developed by the assumption that windows always on from 9 pm to 6 am (https://www.travel-zentech.jp/world/kion/Japan/Temperature_in_Toyama_Prefecture.htm).

3.2. Objective model and internal heat gain
The objective model is a representative unit extracted from an existed multiple dwelling-house with high envelope insulation performance and simplified into the simulation model (Figures 7–8). In order to reproduce the influence of adjacent units on the representative unit, the envelope connected to the surrounding units, ceiling, floor, and partition wall between two units, is set as an adiabatic boundary; envelope directly exposed to the ambient environment are set as a real condition. A cloth-made movable shading device (Figure 9) is set to be used throughout the summer, i.e. June to September.

| Table 2. Characteristics of the different window materials. |
|-------------------------------------------------------------|
| **Index** | **U-value (W/m² K)** | **Solar heat gain coefficient** | **Visible transmittance** |
|-----------|-----------------------|-------------------------------|---------------------------|
| **Real construction** | Win1 | 1.29 | 0.41 | 0.7 |
| | Win2 | 1.2 | 0.41 | 0.67 |
| | Win3 | 1.26 | 0.39 | 0.67 |
| | Win4 | 1.29 | 0.41 | 0.7 |
| | Win5 | 1.29 | 0.37 | 0.7 |
| | Win6 | 1.29 | 0.41 | 0.7 |
| | Win7 | 1.29 | 0.37 | 0.7 |
| | Win1-Win7 | 4.65 | 0.41 | 0.67 |

| Table 3. Equipment and lighting loads of each zone. |
|-----------------------------------------------------|
| **Zone** | **Max equipment Load (W)** | **Max lighting density (W)** |
|-----------|---------------------------|-----------------------------|
| LDK (Living Dining Kitchen) | 274.2 | 45.7 |
| MBR (Main Bedroom) | 80.7 | 37.4 |
| BR (Bedroom) | 79.8 | 25.8 |
| Toilet | 118.7 | 8.6 |

Figure 9. Shading device.
Table 4. Characteristics of the different window.

| Index | Material name          | Window description | U-value (W/m² K) | Solar heat gain coefficient | Visible transmittance |
|-------|------------------------|--------------------|------------------|----------------------------|-----------------------|
| 1     | Single glass           | 6 mm               | 4.9281           | 0.97                       | 0.805                 |
| 2     | Double glass           | 6+ A6 + 6          | 3.2147           | 0.85                       | 0.594                 |
| 3     | Low-e Double GL        | LE6+ A6 + LE6      | 2.6875           | 0.633                      | 0.594                 |
| 4     | Low-e Double GL        | LE6+ A6 + 6        | 2.6216           | 0.37                       | 0.594                 |
| 5     | Low-e Triple GL        | 3+ Ar16 + 3+ Ar16+ LE3 | 1.66605         | 0.288                      | 0.594                 |
| 6     | Double Low-e Triple GL | LE3+ Ar16 + 3+ Ar16+ LE3 | 1.46835         | 0.354                      | 0.594                 |
| 7     | The type of window used in original construction |                    |                  |                            |                       |

Table 5. Descriptions and range of optimized design parameters.

| Variable, 1, and 3 Height, Win1 Width, Win2 Width, Win3 Width, Win4 Width, Win5 Height, Win6 Width, Win7 Height | Variation step | Unit | Range | Distribution |
|-------------------------------------------------------------------------------------------------------------|----------------|------|-------|--------------|
| Win1, 2, and 3 Height                                                                                       | 0.1            | m    | [1,2.5] | discrete     |
| Win1 Width                                                                                                  | 0.1            | m    | [0,1]  | discrete     |
| Win2 Width                                                                                                  | 0.1            | m    | [0,2.4] | discrete     |
| Win3 Width                                                                                                  | 0.1            | m    | [0,2.1] | discrete     |
| Win4 Width                                                                                                  | 0.1            | m    | [0,1.6] | discrete     |
| Win5 Height                                                                                                 | 0.1            | m    | [0,2.4] | discrete     |
| Win6 Height                                                                                                 | 0.1            | m    | [0,1.4] | discrete     |
| Win7 Height                                                                                                 | 0.1            | m    | [0,2.4] | discrete     |

Fixed Point

**Figure 10.** Fixed point and dimensions of each window.

For exploring the influence of combining window design with natural ventilation on buildings with various envelope insulation performance, in addition to the real construction (U-value of external wall is 0.349 W/m² K and details of windows are shown in Table 2) which represents envelope of high-performance building, i.e. Model A. A standard set of envelope material properties (U-value of external wall is 0.4 W/m² K and details of windows are shown in Table 2) is also applied to the objective model to represent the general energy-efficiency building of Japan, i.e. Model B (National Institute for Architecture Research).

On the basis of calibration of site measurement, all the zones except for storage room are equipped with internal heat gain result from equipment, luminaires assumed as light-emitting diode (LED), and metabolism of occupants (Table 3) and the schedule is set according to the measurement results (Building Environment and Energy Conservation Organization 2016). In addition, in order to match the site measurement data, the number of occupants is supposed to be one adult per unit during daytime and nighttime.

In addition, as the decision variables of the optimization framework, the alternate options of window types and variation ranges of window size for a total of seven windows are shown in Tables 4 and 5 in detail. Based on practical considerations, these seven selectable window types in Table 4 all come from actual product parameters of window manufacturers. Due to there is a fixed-layout in the objective model, to suppress the effect of variation of window size, each window is resized based on a fixed point on the lower edge line to ensure that the relative position of the window and the room it serves remain stable (Figure 10). The constraint condition for the window size is that the width is greater than zero and less than the width of the wall, the French window height is greater than 1.8 m and less than the wall height, and the non-French window height is greater than 0 m and less than the wall height.

4. Results

Three parts included in this section show and compare the simulation results of Model A and Model B in different states. Section 4.1 specifically compares the impact of various envelop thermal insulation performance on energy consumption and IEQ under unventilated state. Section 4.2 shows the improvement potential of various natural ventilation for Model A and Model B. Section 4.3

**Figure 11.** Annual energy consumption of Model A and B.
Figure 12. Annual natural indoor temperature of Model A and Model B.

Figure 13. Distribution of natural indoor temperature based on the ATC comfort zone for 80% of the occupants.

Figure 14. Distribution of natural indoor temperature by season based on the ATC comfort zone for 80% of the occupants.

Figure 15. Comfort time ratio of surface indoor temperature during air-conditioned period.

presents improvement potential and optimal solutions of Model A and Model B by coupling window-related parameters adjustment and ventilation usage.

The evaluation indicators of state in Section 4.1 and Section 4.2 are the annual load and thermal comfort which both simulated by Energyplus. The annual load is calculated based on the calculation setting shown in Section 2.4.1 and cooling/heating period introduced in Section 3.1. The thermal comfort consists of two parts, namely, thermal comfort in the free-running state and air-conditioned state and the calculation formula and logic of these two parts has been shown in Section 2.4.2.1 and Section 2.4.2.2 detail.

Section 4.3 shows the multi-objective optimization results obtained by GA optimization and filtered by MCDM. GA belongs to heuristic method rather than mathematical method, so in this study, the screening of optimal solutions is carried out according to the rules of SPEA2’s domination and non-domination principle (Rhinoceros) based on the comparison of value of objective functions. Filtration process of MCDM ensures the elitist of the final result while

| Model   | Winter comfort time (H) | Summer comfort time (H) |
|---------|-------------------------|-------------------------|
| Model A | 1162                    | 219                     |
| Model B | 386                     | 257                     |
emphasizing the diversity of multiple solutions, providing a clear choice guide for designers or stakeholders. In addition, the objective functions of GA appeared in Section 4.3 includes daylight environment in addition to the above-mentioned annual load and thermal comfort. $D_A$ is the evaluation value of the daylight environment and its calculation logic is shown in Section 2.4.3.

Referring to the occupancy schedule of Japanese residents (Grasshopper), the objective function of thermal comfort in free-running state is only applied to LDK, and scopes of the other three objective functions are defined as all range of objective model.

\[ \begin{align*}
\text{Load (kWh)} & \\
\text{no ventilation} & 1848.2 & 1164.1 & 0.0 \\
\text{ventilation pattern 1} & 1266.1 & 1164.6 & 1164.1 \\
\text{ventilation pattern 2} & 1792.7 & 423.2 & 1164.5 \\
\text{ventilation pattern 3} & 419.4 & 2200.0 & 2200.0 \\
\end{align*} \]

**Figure 17.** Energy consumption for each ventilation pattern in Model A.

4.1. Energy consumption and IEQ of objective model without ventilation

Compared with Model B, high envelope thermal insulation performance of Model A significantly reduces the heating load while slightly increases the cooling load (Figure 11). Although the annual energy consumption of the Model A decreased by 667 kWh compared with that of Model B, the low heat loss of high thermal performance envelope combined with internal heat gain is gradually increasing the risk of rising cooling load during the cooling period, and this problem is easily overlooked when only analyzing the annual energy consumption.

Furthermore, due to improvement of the envelope, the annual natural temperature of Model A rises substantially compared with Model B under free-running state (Figure 12). Although model A has less time below lower limit of ATC model than model B, and the time over upper limit is greatly increased (Figures 13 and 14). Meanwhile, under the air-conditioned state, high thermal insulation performance of envelope of Model A results in relatively high external surface (external wall and window) indoor temperature throughout the air-conditioned period. Therefore, the time ratio of each external surface indoor temperature within the operative temperature comfort zone of Model A is increased compared with that of Model B in winter while deteriorated in summer (Figure 15). The average radiant thermal comfort time of all test points in Model A is 576 hours more than that of Model B during winter but 38 hours less during summer. In general, the annual thermal comfort in air-conditioned state of Model A is improved compared to Model B (Table 6).

Consequently, based on the analysis of the annual energy consumption value and thermal comfort, enhancement of envelope thermal insulation performance is undoubtedly a wise passive energy-saving strategy, but it also means the sacrifice of energy consumption performance and thermal comfort performance in summer and transition season. Coupled with the trend of global warming, the compromise between the advantages and disadvantages of this approach will undoubtedly need to be reconsidered.

\[ \begin{align*}
\text{Summer natural indoor temperature distribution} & \\
\text{ventilation pattern 1} & 2290 & 555 \\
\text{ventilation pattern 2} & 2559 & 367 \\
\text{ventilation pattern 3} & 2247 & 594 \\
\text{Unventilated state} & 2274 & 329 \\
\end{align*} \]

\[ \begin{align*}
\text{Transition season natural indoor temperature distribution} & \\
\text{ventilation pattern 1} & 2144 & 432 \\
\text{ventilation pattern 2} & 2229 & 342 \\
\text{ventilation pattern 3} & 2798 & 293 \\
\text{Unventilated state} & 1965 & 293 \\
\end{align*} \]

**Figure 18.** Distribution of natural indoor temperature of each ventilation pattern of Model A based on the ATC comfort zone for 80% of the occupants.
4.2. **Effect of natural ventilation**

In the climate of Kurobe, the ventilation time of the three ventilation patterns introduced in the Section 2.3 is shown in Figure 16. Due to the natural ventilations that do not occur in heating period, there is little change in energy consumption and thermal comfort both of Model A and Model B during winter (heating season) before and after ventilation.

4.2.1. **Effect of natural ventilation for Model A**

During cooling season, ventilation pattern ① and ③ which use nocturnal ventilation significantly reduce the cooling load while pattern ② that use daytime ventilation only reduces cooling load by 55 kWh (Figure 17). Furthermore, ventilation pattern ③ obtained the best cooling energy consumption reduction effect since it also uses nocturnal ventilation during the transition season resulting in the indoor temperature during the start of heating period is lower than that of other states.

Meanwhile, nocturnal ventilation also significantly improves the thermal comfort in the free-running state during summer. The time that natural indoor temperature within the ATC comfort zone of pattern ① and ③ is almost 15 times that of unventilated state, while the comfort time pattern ② is only twice that of the unventilated state (Figure 18). During transition season, the nocturnal ventilation results in most of the time the natural indoor temperature lower than ATC lower limit, whereas daytime ventilation increases the time within ATC comfort zone by 300 hours (Figure 18). Combined with summer and transition season, pattern ① creates the optimal natural indoor temperature.

In air-conditioned state, these natural ventilation patterns effectively lower the external surface temperature in summer and increase the time ratio of external surface temperature within operative temperature comfort zone (Figure 19), and the average radiant thermal comfort time of all test points in pattern ① and ③ increased by 1141 hours and 1096 hours compared to unventilated state, and pattern ② is only 104 hours more (Figure 20).

According to the comparison results of before and after ventilation, natural ventilation dramatically improved the energy consumption performance and thermal comfort of Model A in summer and caused a minor improvement of thermal comfort in transition season, meanwhile, which significantly alleviated the overheating. And, as can be seen from the results, ventilation not only improves the thermal comfort and energy consumption performance by improving the room temperature, it is also crucial to improve the external surface indoor temperature. From the results, it can be seen that for residential buildings with high thermal insulation performance, various design strategies that can effectively improve the internal surface temperature of the external walls still need further study. Compared with the other two ventilation patterns, pattern ① is more suitable for Model A.

4.2.2. **Effect of natural ventilation for Model B**

The decreasing trend of cooling load in model B caused by natural ventilation is the same as that in Model A, but the decrease is smaller than that in Model A (Figure 21).
Figure 22. Natural indoor temperature distribution of each ventilation pattern of Model B based on the ATC comfort zone for 80% of the occupants.

Figure 23. Time ratio of each surface indoor temperature within OP comfort zone of Model B in ventilation state during summer.

Figure 24. Radiant thermal comfort time of Model B in ventilation state.

Meanwhile, natural ventilation also significantly improves the thermal comfort in free-running state during summer for Model B, the time that natural indoor temperature within the ATC comfort zone of patterns ① and ② almost tripled unventilated state while comfort time of pattern ③ almost same as the unventilated state. During transition season, patterns ① and ② caused a minor decrease of time within ATC comfort zone and pattern ③ resulted in the comfort time significantly decrease compared to the unventilated state (Figure 22).

Figure 25. Convergence of optimization for Model A.

Figure 26. Convergence of optimization for Model B.

Similar to Model A, these natural ventilation patterns also improve the thermal comfort of air-conditioned state of Model B by increasing the time ratio of external surface temperature within the
operative room temperature comfort zone during summer (Figure 23). In addition, the increase of radiant thermal comfort time caused by nocturnal ventilation (pattern ① and pattern ③) in Model B and Model A is similar while the improvement by daytime ventilation (pattern ②) in Model B is better than that of Model A (Figure 24).

The above results show that the relatively poor external wall insulation performance of model B leads to high cooling room load, but it can ensure a relatively comfortable room temperature and internal surface temperature of the external wall in the transition season and summer, but this also limits improvement effect brought by natural ventilation. Therefore, in the current trend of high-performance residential development, compared with the traditional thermal insulation structure, the advantages of high-performance thermal insulation structure can be seen at a glance in winter in the cold zone and temperate zone, but its disadvantages will become more and more significant in the transition season and summer in the temperate zone, and more passive energy-saving measures such as natural ventilation are required to cooperate to seek benefits and avoid disadvantages. Compared with the other two ventilation patterns, pattern ① is more suitable for Model B.

### 4.3. Optimal results

The optimization process in this study is completed based on the Genetic algorithm (GA) loaded in the Octopus, and the elitism is set as 0.5, the crossover rate is set as 0.8, the mutation rate is set as 0.5, the probability of mutation of each genome is set as 0.1. Considering the simulation cost and relatively high mutation rate, the population size is set as 30, and the max generation is 50. Since this study contains four objective functions, it is difficult to show the final pareto front in 3D graphics. Therefore, the convergence of optimization for Model A and Model B is shown in the form shown in Figures 25–26. The first vertical axis to the fourth vertical axis represents the objective function of load temperature, thermal comfort in free-running state, sDA and thermal state in air-conditioned state, respectively. As shown in the figure, the target values of the final solution converge greatly.

#### 4.3.1. Optimal results of Model A

The optimization framework developed in this study was implemented to optimize the window size and window type of Model A in the state of natural ventilation pattern ①. The details of final chosen characteristic optimal cases based on the selection logic (MCDM) proposed in Section 2.6 for Model A are shown in the Tables 7,8,9, and all four objective functions of these cases were optimized to a small extent simultaneously. However, none of the optimal cases met the filter requirements of the criterion of Comfort & Daylight preferred, due to a good light environment requires a larger window area which also leads to the deterioration of indoor thermal comfort, especially the radiant thermal environment.

In addition, the total area of the south windows of these chosen cases almost unchanged or increased slightly, and the total area of north windows decreased to varying degrees (Tables 10–11). Although all four objective functions of chosen cases have been
Table 9. Geometry of each optimal case of Model A.

|                  | Original | Load and Daylight preferred | Load and Comfort preferred |
|------------------|----------|----------------------------|---------------------------|
|                  |          | Optimal case 1             | Optimal case 2            | Optimal case 3 |
| Optimal case 1   |          |                            |                           |
| Optimal case 2   |          |                            |                           |
| Optimal case 3   |          |                            |                           |

Table 10. Window area of optimal cases based on the Load and Daylight preferred.

|                  | Original | Optimal case 1 | Optimal case 2 | Optimal case 3 |
|------------------|----------|----------------|----------------|----------------|
| Total Area of South Window (㎡) | 13.20    | 13.72          | 13.60          | 14.52          |
| Total Area of North Window (㎡)  | 5.66     | 5.00           | 5.15           | 4.86           |
| Total Area of All Window (㎡)   | 18.86    | 18.72          | 18.75          | 19.38          |

Table 11. Window area of optimal cases based on the Load and Comfort preferred.

|                  | Original | Optimal case 1 | Optimal case 2 | Optimal case 3 |
|------------------|----------|----------------|----------------|----------------|
| Total Area of South Window (㎡) | 13.20    | 13.00          | 13.00          | 13.82          |
| Total Area of North Window (㎡)  | 5.66     | 4.32           | 4.17           | 3.16           |
| Total Area of All Window (㎡)   | 18.86    | 17.32          | 17.17          | 16.98          |

Figure 27. Energy flow of each window in LDK before and after optimization in winter.

Optimized, some types of windows of chosen optimal cases were replaced by ones with poor U-value, especially the middle window on the south wall of LDK, i.e. the window 2, and the WWR also increased at the same time.

Figure 28. Time ratio of each surface indoor temperature within operative temperature of case 1’s LDK during winter.

Figure 29. Energy flow of each window in LDK before and after optimization in summer.

Figure 30. Time ratio of each surface indoor temperature within operative temperature of case 1’s LDK during summer.
Figure 31. Energy flow caused by natural ventilation before and after optimization in summer.

Table 12. Geometry of each optimal case of Model B.

|          | Load and Daylight preferred | Load and Comfort preferred |
|----------|----------------------------|---------------------------|
|          | Optimal case 1              | Optimal case 2            | Optimal case 3 |
|          | Optimal case 1              | Optimal case 2            | Optimal case 3 |
|          | Optimal case 2              | Optimal case 3            |
|          | Optimal case 3              |

Table 13. Optimal cases based on the Load and Daylight preferred.

|          | Original | Optimal case 1 | Optimal case 2 | Optimal case 3 |
|----------|----------|----------------|----------------|----------------|
| Win1 Material index | 7        | 2              | 2              | 2              |
| Win2 Material index | 7        | 7              | 7              | 7              |
| Win3 Material index | 7        | 2              | 2              | 2              |
| Win4 Material index | 7        | 5              | 5              | 5              |
| Win5 Material index | 7        | 7              | 7              | 7              |
| Win6 Material index | 7        | 6              | 6              | 6              |
| Win7 Material index | 7        | 5              | 5              | 5              |
| Win1&2&3 Height(m)  | 2.25     | 2.44           | 2.44           | 2.44           |
| Win1 Width(m)       | 0.78     | 0.85           | 0.85           | 0.83           |
| Win2 Width(m)       | 2.4      | 2.37           | 2.37           | 2.37           |
| Win3 Width(m)       | 1.87     | 1.8            | 1.8            | 1.78           |
| Win4 Width(m)       | 0.78     | 0.12           | 0.12           | 1.12           |

Table 13. (Continued).

|          | Original | Optimal case 1 | Optimal case 2 | Optimal case 3 |
|----------|----------|----------------|----------------|----------------|
| Win4 Height(m) | 2.45     | 2.44           | 2.45           | 2.44           |
| Win5 Width(m) | 1.6      | 2.35           | 2.31           | 2.35           |
| Win5 Height(m) | 1.15     | 1.34           | 1.34           | 1.34           |
| Win6 Width(m) | 0.78     | 1.52           | 1.55           | 1.48           |
| Win6 Height(m) | 2.45     | 2.05           | 2.05           | 2.05           |
| Win7 Width(m) | 1.6      | 2.24           | 2.24           | 2.24           |
| Win7 Height(m) | 1.15     | 1.37           | 1.37           | 1.37           |
| Load(kWh)      | 2591.3   | 1819.8         | 1821.0         | 1845.6         |
| Time ratio within ATC comfort zone | 48.90% | 55.53% | 55.53% | 55.75% |
| Time ratio within OT comfort zone | 32.90% | 49.94% | 49.94% | 50.17% |
| sDA            | 14.80%   | 25.00%         | 24.38%         | 25.00%         |

Table 14. Optimal cases based on the Load and Comfort preferred.

|          | Original | Optimal case 1 |
|----------|----------|----------------|
| Win1 Material index | 7        | 2              |
| Win2 Material index | 7        | 7              |
| Win3 Material index | 7        | 2              |
| Win4 Material index | 7        | 5              |
| Win5 Material index | 7        | 5              |
| Win6 Material index | 7        | 7              |
| Win7 Material index | 7        | 5              |
| Win1, 2, and 3 Height (m) | 2.25   | 1.92           |
| Win1 Width (m) | 0.78     | 0.63           |
| Win2 Width (m) | 2.4      | 2.37           |
| Win3 Width (m) | 1.87     | 1.78           |
| Win4 Width (m) | 0.78     | 0.14           |
| Win4 Height (m) | 2.45     | 2.42           |
| Win5 Width (m) | 1.6      | 2.36           |
| Win5 Height (m) | 1.15     | 1.26           |
| Win6 Width (m) | 0.78     | 1.54           |
| Win6 Height (m) | 2.45     | 2.07           |
| Win7 Width (m) | 1.6      | 2.18           |
| Win7 Height (m) | 1.15     | 0.97           |
| Load (kWh)      | 2591.3   | 1860.3         |
| Time ratio within ATC comfort zone | 48.90% | 58.57%         |
| Time ratio within OT comfort zone | 32.90% | 50.88%         |
| sDA            | 14.80%   | 17.90%         |

To analyze the above situation in detail, the LDK of Case 1 of Load and Comfort preferred was exemplified.
Table 15. Window area of optimal cases based on the Load and Daylight preferred.

|               | Original | Optimal solution 1 | Optimal solution 2 | Optimal solution 3 |
|---------------|----------|--------------------|--------------------|--------------------|
| Total Area of | 13.20    | 15.40              | 15.34              | 15.15              |
| South Window  |          |                    |                    |                    |
| Total Area of | 5.66     | 6.48               | 6.54               | 6.40               |
| North Window  |          |                    |                    |                    |
| Total Area of | 18.86    | 21.88              | 21.88              | 21.55              |
| All Window    |          |                    |                    |                    |

Table 16. Window area of optimal cases based on the Load and Daylight preferred.

|               | Original | Optimal solution 1 |
|---------------|----------|--------------------|
| Total Area of | 13.20    | 12.15              |
| South Window  |          |                    |
| Total Area of | 5.66     | 5.64               |
| North Window  |          |                    |
| Total Area of | 18.86    | 17.79              |
| All Window    |          |                    |

In winter, although the deterioration of U-value leads to the increase of heat loss, the increase of SHGC and slight increase of the total area of south windows greatly boosts the heat gain resulting from the increase of amount of solar radiation entering the room (Figure 27) which effectively increased the indoor temperature and internal surface temperature. Therefore, the time ratio that indoor surface temperature of external walls and windows within the OT comfort zone was greatly improved (Figure 28), the time ratio that natural temperature within the ATC comfort zone was also increased (571 hours of original state to 1096 hours of optimal case), and heating load was decreased (1164 kWh of original state to 1031 kWh of optimal case). In summer, the larger window of optimal cases combined with appropriate natural ventilation pattern increased the heat loss (Figure 29). Moreover, the shading device effectively suppressed the increase of heat gain caused by the increase of window size and SHGC (Figure 30). Combining the cooling effect of ventilation and the use of shading, the time ratio that indoor surface temperature of external walls and windows within the OT comfort zone was slightly increased (Figure 31). This result breaks the traditional high-performance building design logic, which proves that under ventilation, properly reducing the window’s thermal insulation performance and improving SHGC will achieve thermal environment improvement in the current climate.

With the optimization of energy consumption and thermal comfort, the window area of the optimal solution was increased, and in a certain area, the position of the upper edge of the window was raised by adjusting the width and height. In addition, as the window type changing during the optimization process, the visual transmittance was also improved. Based on the above conditioned, the indoor daylight environment was also significantly improved, i.e. the value of sDA is improved; therefore, the feasibility of jointly improving the daylight environment and the thermal environment has been proved.

4.3.2. Optimal results of Model B

The optimization framework developed in this study was also implemented to optimize the window size and window type of Model B in the state of natural ventilation pattern (1). The final chosen characteristic optimal cases based on the selection logic for Model B are shown in Tables 12, 13, 14. Compared to Model A, the extent of improvement of all four objective functions of Model B is much greater, and the optimization framework significantly reduced the performance gap between Model B and Model A. However, due to the relatively poor insulation performance of external wall limits the optimization potential, just one optimal case met the screening requirements of Load & Daylight preferred, and none of the optimal cases met the filter condition of the criterion of Comfort & Daylight preferred same as Model A.

In addition, the total area of south windows of these optimal cases of Model B almost unchanged or increased slightly, and the total area of north windows increased to varying degrees (Tables 15–16). The same reason for Model A optimizes, although some types of windows of chosen optimal cases were replaced by ones with poor U-value, and the WWR also increased, all four objective functions of chosen cases also were optimized simultaneously.

5. Conclusions

Using a three-phase consisted optimization framework detailedly shown in Section 2.1, this study examined the impact of natural ventilation and architectural window design has on the simultaneous optimization of energy consumption, thermal comfort, and daylight environment of buildings located in a temperate climate zone in Japan. In addition, by comparing the effects of different natural ventilation methods on overheating problems to propose ventilation suggestions, this study also discusses the effect of passive energy-saving behavior of humans on the optimization potential of large-scale computational spatial search algorithms.

As a prerequisite, this study first compares the environmental performance of the residential building under unventilated state with ordinary thermal insulation performance and high thermal insulation performance, and discusses the overheating risks faced by high-thermal-insulation residential in temperate climate zones and the environmental problems caused by overheating. There are some obvious general trends between the two models, most notably: (1) For the residential buildings in the temperate zone, the improvement of the insulation performance of the building envelope significantly reduces the annual
energy consumption, while also causes increase of cooling load, and deterioration of thermal comfort in transition season, namely increases the risk of overheating phenomenon. (2) Combined with the rising temperature trend in the future, the overheating problem can be predicted to become more serious in high-performance buildings, and even in buildings in cold climate regions. (3) The trade-off between the advantages and disadvantages brought by the high-performance envelope should be transformed into the core research problem.

To explore the potential of passive cooling technology to solve overheating, nature ventilation is conducted into the optimization framework in Phase 1. By naturally ventilating the models with the two sets of thermal insulation envelopes, several common trend that exists in both two model are obvious: (1) Nature ventilation significantly alleviates overheating. (2) On the basis of the climatic characteristics of the location of the case study, nocturnal ventilation has the best effect of reducing energy consumption and improving thermal comfort during summer but causes poor thermal comfort environment in transition season. (3) Compared with the nocturnal ventilation, the daytime ventilation in the transition season has achieved a great degree of thermal comfort improvement through the compromise of small energy consumption reduction. These common trends mean that when considering the use of ventilation to simultaneously solve the energy consumption and thermal comfort problems caused by overheating, the complex and variable composite natural ventilation method needs to be studied in detail to explore the compromise between the two. For buildings in temperate zone, the development of smart window operating systems has great potential and value. In addition, nature ventilation has significantly higher energy consumption improvement potential and a slightly higher thermal comfort improvement potential for buildings with high thermal insulation performance, one of the main reasons for this situation is that the high-thermal-insulation model has a higher heat storage capacity of envelope. Therefore, in temperate and even cold regions with large daily temperature differences, it is of great value to study the use of high heat storage materials in high-insulation buildings coupled with passive cooling technology to solve the problem of overheating.

In addition, the near-optimal results of produced by GA (Phase 2) and filtered by MCDM (Phase 3) in this study prove the universality of multi-objective optimization framework in the face of buildings with different thermal insulation performance. The building with high thermal insulation performance (the real condition of case study) shows relatively low optimization potential of energy consumption; nevertheless, in the optimization of thermal comfort and light environment, it shows almost the same optimization potential as the buildings with normal thermal insulation performance. This means that the original case study used in this research already has an excellent energy consumption performance before optimization and the achievement has not sacrificed the performance of other physical environments. Compared with the result of traditional design method, this achievement has been improved obviously. (1) The physical environment based on this achievement still has obvious improvement potential after the confirmation of GA results; therefore, the results of the second phase of the optimization framework strongly show the necessity of using algorithms to conduct high-precision searches in huge computing spaces under the high-performance building development trend. (2) The optimization results also show a trend that, natural ventilation improves the importance of heating energy consumption and thermal comfort in winter by greatly optimizing the thermal environment in non-winter and cooling energy consumption. (3) Due to consistency of the trend of visible light and infrared that can bring heat, natural ventilation effectively improves potential for simultaneous optimization of the light and thermal environments (annual energy consumption and thermal comfort in cooling period). Therefore, the research and development of more complex ventilation patterns will bring a wider development space for the optimization framework which uses window-related elements as decision variables.

In general, the use and research of passive cooling technology and algorithms for high-precision search in a huge computing space are crucial for the development of high-performance residences, and the combination of these two can effectively further expand the optimization of high-performance buildings and open up new research ideas.

Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| ACH          | adaptive thermal comfort |
| AT           | air temperature |
| ATC          | air changes per hour |
| DA           | daylight autonomy |
| EPBD         | energy performance of buildings directive |
| GA           | genetic algorithm |
| HVAC         | Heating, Ventilation and Air Conditioning |
| IEQ          | indoor environmental quality |
| LDK          | living dining kitchen |
| LED          | light-emitting diode |
| MCDM         | Multi-Criteria Decision-Making |
| MRT          | mean radiant temperature |
| NSGA-II      | non-dominated-and-crowding Sorting Genetic Algorithm II |
| nZEH         | nearly zero-energy houses |
| OT           | operative temperature |
| OF           | objective function |
| POE          | post-occupational evaluations |
| sDA          | spatial Daylight Autonomy |
SHGC  solar heat gain coefficient
SPEA2  Strength Pareto Evolutionary Algorithm II
T_{\text{DO}}  indoor comfort temperature
T_{\text{m}}  prevailing mean outdoor temperature
T_{\text{o}}  operative temperature
T_{\text{r}}  air temperature
T_{\text{m}}  mean radiant temperature
T_{\text{N}}  surface temperature of surface N
\text{FA}_N  angle factor between a person and surface N
VT  visual transmittance
WWR  window-wall-ratio
ZEH  zero-energy houses

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