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Creating sustainable industrial building in China by lowering energy use and improving the working environment

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by

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Abstract

Over 70% of energy in China is consumed by industrial buildings and related support activities. In order to reduce production costs, owners of factories tend to pay little attention to protecting the environment or workers' health, causing many serious consequences. Poorly designed buildings require more energy to operate and are less energy efficient to maintain. A lack of natural lighting results in more energy consumption for interior illumination, and improper fenestration design requires more energy to keep buildings cool. An uncomfortable working environment will affect the working efficiency and physical health of the labor force. In this thesis, two simple, passive strategies—daylighting and passive cooling for factory buildings—are studied and tested separately, aiming to reduce energy consumption and improve the working environment. The study location selected is in the Shanghai suburban area. The object of the study is a typical, old manufacturing plant that is still in use, which represents the majority of industrial buildings in China. Instead of rebuilding the entire industrial building construction, renovating existing industrial buildings, by applying a passive strategy, has huge potential to save energy and improve the working environment. Whether and how much these passive strategies can reduce energy consumption of existing industrial buildings and improve the working environment will be explored by comparing existing data analysis to a renovated building data analysis.

Table Contents

I. Introduction

Today, people from all parts of the world are facing a serious shortage of energy resources. More research is being conducted on energy resources analysis in the hope of understanding the global situation, and what should be done to protect energy resources. Many studies emphasize the importance of using more renewable resources to replace traditional resources. In recent decades, renewable energy, such as solar and wind power, have become a common and major energy resource within industry in Economic Co-operation and Development (OECD) countries. The total amount of renewable energy will peak and then cease to grow after 2025. As for non-OECD countries, even though they have begun to use renewable energy, they still rely heavily on traditional energy resources, such as oil, coal, and natural gas. In addition, non-OECD countries are predicted to maintain high economic growth rates until 2040, and their overall traditional energy consumption level will therefore continue to increase. [1] Poor working conditions, such as child labor, working overtime, less pay, and health issues are common in non-OECD countries. This situation is becoming worse because of a lack of management and little attention from society. In this thesis, China has been selected to represent non-OECD countries.

[1] Imboden, Dieter M., and Carlo C. Jaeger. "Towards a sustainable energy future." Energy: The Next Fifty Years (1999): 63-94.

II. Literature Review

1. Industrial building energy consumption statement

"In 2003, China became the world's second largest energy consumer behind the United States. China took over for 31% of world coal consumption, 7.6% of oil consumption, 10.7% hydro-electricity consumption and 1.2% gas consumption."[2] These numbers continue to increase along with China's GDP growth. According to the Energy Efficiency & Renewable Energy Organization, "in 2010, China replaced the United States as the largest consumer of energy in the world."[3] China consumed 20% of world energy, a significant proportion—with 70% of this energy consumed by industrial buildings. Between 2003 and 2010, rapid growth of China's energy consumption level and its GDP was witnessed. However, its high energy intensity suggests a less than optimistic situation. According to a report on energy intensity (measured as units of energy per unit of GDP) provided by Enerdata for the same time period, China maintained a high average energy intensity of 0.194 koe/$2005p (kilo of oil equivalent/GDP at constant 2005$ PPP), ranking eighth highest for energy intensity globally, while the United States only has 0.14 koe/$2005p of energy intensity. This result indicates a very low energy consumption efficiency for China. It is clear that basing Chinese energy consumption on industrial usage causes concern as "Study shows that natural gas takes the largest proportion of energy consumption in industrial building, while electricity ranks the second."[4] Nevertheless, in China most electricity is generated from the conversion of primary sources of energy, such as fossil fuels (coal, natural gas, and oil). Further, factories in China are heavily reliant on traditional energy resources. The demand for natural gas in industrial buildings is mostly driven

[2] Crompton, Paul, and Yanrui Wu. "Energy consumption in China: past trends and future directions." Energy economics 27, no. 1 (2005): 195-208.
[3] http://buildingsdatabook.eren.doe.gov/ChapterIntro1.aspx?1#1
[4] http://www.eia.gov/energyexplained/index.cfm/data/index.cfm?page=us_energy_industry

by machine operation, and it is difficult to reduce this kind of energy consumption. However, in this paper this matter will not be discussed in detail. Rather, the study will focus on how to use renewable energy to replace traditional electricity for both space illumination and space cooling within factory buildings, to reduce energy consumption and increase energy efficiency, whilst improving the working environment.

2. Working environment in industrial building

Although companies are profit-driven organizations, they should also be socially responsible in terms of employees' health. However, in the pursuit of profitability and rapid growth, many Chinese companies fail to realize this responsibility, with their workers employed in intolerable working conditions. A pleasant working environment does not only impact positively on workers' morale and foster employee commitment, but also helps to maintain a stable workforce who remain with the company, whilst additional workers are attracted to join. Conversely, a poor working environment increases the possibility of "illness, rehabilitation, personnel turnover, production stoppages, and damages of equipment, poor quality, and underutilized potential."[5] For example, the effect of global warming has caused the average temperature in Shanghai to increase by 7.77 °C since 1980. During hot seasons (when factory workers suffer from these high temperatures), heat radiation from a machine and the metabolic level make the working environment even more intolerable. Additionally, a lack of sufficient air exhaust is very common in China's industrial buildings. "If the possibility of reaching cooler air is not sufficient, and the air is not moving quickly, heat strain and heat stroke could appear."[6] As a result, a worker's physical working capacity[7] and mental task ability will decrease.[8] Another factor that affects workers' productivity is the level of illumination. However, few industrial buildings in China offer sufficient interior lighting to provide a safe and comfortable working environment. As Corwin Bennett stated in his book "*Human Factor in Design*," all design goals

[5] http://www.swerea.se/en/areas-of-expertise/production-systems/work-environment

[6] Ramsey JD, Bernard TE. Heat stress. Chapter 22. In: Harris RL, ed. Patty's industrial hygiene, 5th edition. New York: John Wiley and Sons; 2000, pp. 92584

[7] Kerslake, D. McK. The stress of hot environments. Vol. 29. CUP Archive, 1972.

[8] Ramsey JD. Task performance in heat: a review. Ergonomics 1995; 38: 154-165.

are affected by illumination. "Luminous environment produces a positive impact on occupants, while low levels of illumination could lead to eye strain."[9]

[9] Bennett, Corwin. Spaces for people: Human factors in design. Prentice-Hall, 1977.

3. Hypothesis design solution

3.1. Natural Daylighting and Illumination Energy Consumption

It has been demonstrated by one study that workers in “green” factories are more productive due to "higher illumination, greater access to outside view, better thermal control, and less airborne particulates."[10] When the valid lighting increased from about 15 to 100 foot-candles, the frequency of accidents dropped by 50%.[11] Using daylighting can improve visual comfort and reduce building energy consumption, especially electricity usage. Energy saving can be achieved by using more natural daylight in industrial buildings. According to a field study conducted in large industrial buildings in Tianjin, China, "using the technique of dimming control integrated with daylighting, more energy can be saved than using the traditional On/Off control of artificial lighting. Electricity saving potential for the On/Off control and the dimming control integrated with daylighting were 36.1% and 41.5%."[12] Window type, glazing type, window size and location effect both on daylighting and thermal performance of office buildings.[13] For example, by incorporating more natural daylight, a factory with a 30% window-to-wall ratio on the south side is able to obtain 500 lux on the work plane for 76% of the year. "Proper top lighting with no over glaring and heat can help to reduce the energy demand for electric lighting."[14] One study used field measurements and computer simulation for a factory building in Tianjin, China. Results suggested that the electricity saving potential was appreciable. "The use of artificial sky LED can satisfy building performance and introduce a

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[10] Ravindu, Sachinthaka, Raufdeen Rameezdeen, Jian Zuo, Zhihua Zhou, and Ravihansa Chandratilake. "Indoor environment quality of green buildings: case study of an LEED platinum certified factory in a warm humid tropical climate." Building and Environment 84 (2015): 105-113.

[11] Bennett, Corwin. Spaces for people: Human factors in design. Prentice-Hall, 1977.

[12] ChenJunjie Liu, Jingjing Pei, Xiaodong Cao, Qingyan Chen, and Yi Jiang.Yuanyi,. “"Experimental and simulation study on the performance of daylighting in an industrial building and its energy saving potential.” Energy and Buildings 73, 2104: 184-191.

[13] Tzempelikos, Athanassios, and Andreas K. Athienitis. "The impact of shading design and control on building cooling and lighting demand." Solar Energy 81, no. 3 (2007): 369-382.

[14] Verso, Valerio RM Lo, Stefano Invernizzi, Antonio Carlin, and Andrea Polato. "Towards the factory of the future: A new concept based on optimized daylighting for comfort and energy saving." In Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on, pp. 701-706. IEEE, 2015.

great amount of daylight to the indoor environment. This strategy can both help with energy saving especially electricity consumption and comfort enhancement."[15]

[15] Chen, Yuanyi, Junjie Liu, Jingjing Pei, Xiaodong Cao, Qingyan Chen, and Yi Jiang. "Experimental and simulation study on the performance of daylighting in an industrial building and its energy saving potential." Energy and Buildings 73 (2014): 184-191.

3.2. Natural Ventilation and Cooling Energy Consumption

In 2011, Homma and Matsumoto completed their study that indicated how a naturally ventilated cavity roof has significant potential in improving the indoor thermal environment, and can help to cut energy consumption of factory buildings. The authors developed a computer program to investigate the effect of this cavity ventilation, by comparing one factory with a cavity roof with a single-roofed factory. Their results revealed that the cavity roof outperformed the traditional single roof in lowering the operative temperature by approximately 4.4 °C. If a factory uses the heating, ventilation, and air conditioning (HVAC) system to maintain the design temperature (26 °C), the saving achieved in cooling loading could reach 50% of energy consumed during summer time by using cavity roof.[16] A combination of active cooling systems and natural passive ventilation solutions has the potential to reduce temperature levels as well as cooling loads. [17] As a result, operation cost can be reduced too. "Shading control has the highest impact on reducing cooling energy demand. South side of building need to be shaded in order to effectively reduce cost by the cooling load."[18] The reason why the workforce in industrial buildings suffers from high temperatures more than employees in other type of buildings is that heat generated from facilities inside the factory is not able to be released, as pointed out by Kang and Lee.[19] In their study, researchers tried to cool down the interior space by creating natural ventilation with a different angle of louvered ventilators, which affects the indoor air flow differently.

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[16]Susanti, L., H. Homma, and H. Matsumoto. "A naturally ventilated cavity roof as potential benefits for improving thermal environment and cooling load of a factory building." Energy and Buildings 43, no. 1 (2011): 211-218.

[17] Taleb, Hanan M. "Natural ventilation as energy efficient solution for achieving low-energy houses in Dubai." Energy and Buildings 99 (2015): 284-291.

[18] Tzempelikos, Athanassios, and Andreas K. Athienitis. "The impact of shading design and control on building cooling and lighting demand." Solar Energy 81, no. 3 (2007): 369-382.

[19] Kang, Jong-Hoon, and Sang-Joon Lee. "Improvement of natural ventilation in a large factory building using a louver ventilator." *Building and Environment*43, no. 12 (2008): 2132-2141.

4. Case study

4.1. Automated Warehousing Facility / 2014

The warehouse indicated in Figure 1 is a traditional, brick building located in Delhi, India. The location has an extreme climate, which requires a great deal of energy to reduce temperatures to human comfort levels. This warehouse is divided into 3 parts: warehouse, loading bay, and office space. A comprehensive environmental and energy strategy is essential to maintain a comfortable occupancy throughout the year. Rather than increasing a thick building envelope, a perforated brickwork screen is installed over the window base facade. The innovation strategy is to improve thermal mass and natural ventilation. This brick screen shades both glazed and windows facades, set back approximately 1200 mm. This helps to create a buffer zone that cuts glare and reduces direct heat gain. This strategy significantly reduced the cooling loading. Figure 2 demonstrates how the brick screen improves and controls the interior air movement. The glazed barrier can be opened during good weather when natural ventilation is useful, and closed during high temperature period for a mechanical cooling system. After this building was erected, a site survey was taken to record the achievement of the design strategy. Results show that the maximum difference between the exterior and interior spaces is 10 °C. [20]

This design strategy is successful in blocking over glazed and direct solar heat. In this case study, the warehouse applied two simple, basic passive strategies to help reduce the building energy use. Operable screen shades help to block direct solar heat gain, and hence provide passive ventilation. Additionally, having more daylight and access to fresh air help to create a comfortable working environment.

[20] "Automated Warehousing Facility / AKDA" 13 Oct 2016. ArchDaily. Accessed 10 Dec 2018. <https://www.archdaily.com/797222/automated-warehousing-facility-akda/> ISSN 0719-8884

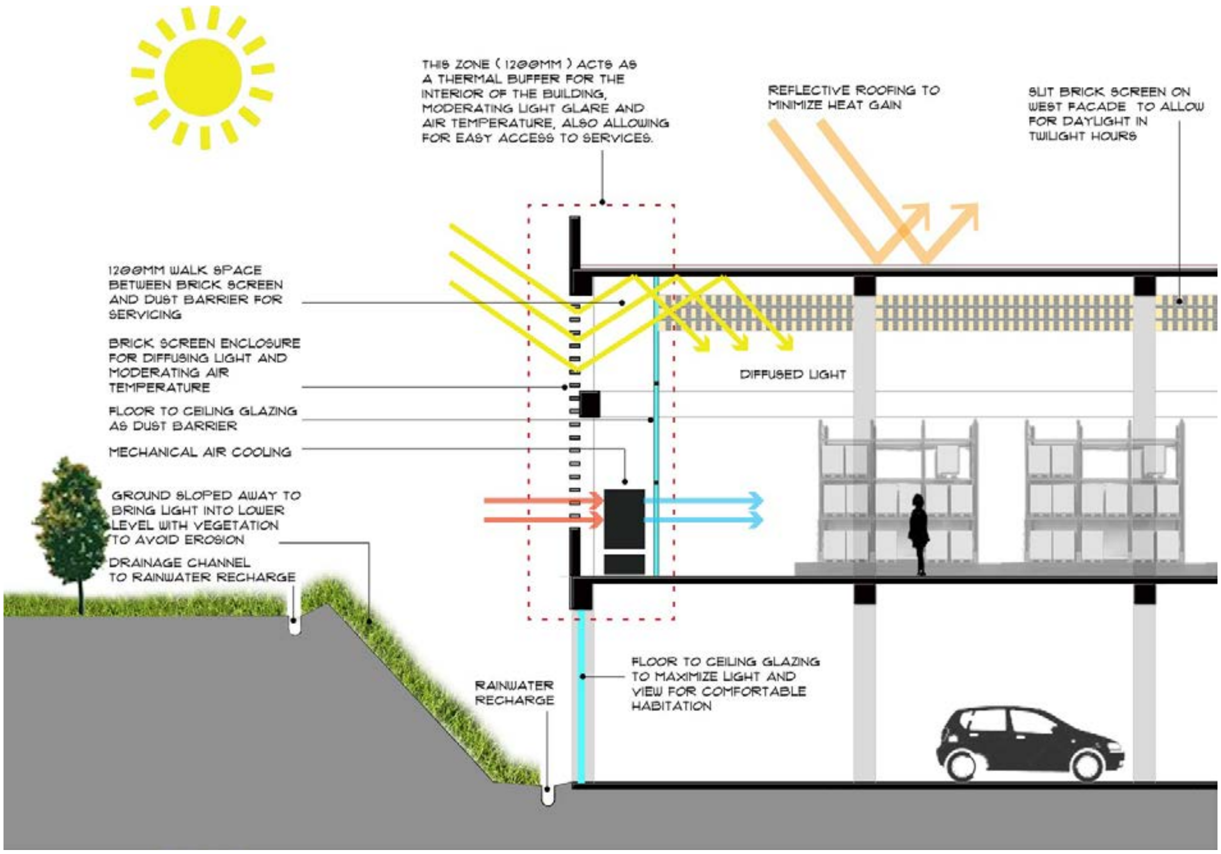


Figure 1 Automated Warehousing Facility Brick screen

Figure 2 Automated Warehousing Facility Natural ventilation

4.2. Cross Ventilation, the Chimney Effect and Other Concepts of Natural Ventilation

Wind is a natural, free, renewable and healthy resource to improve the thermal comfort of buildings. Architects and engineers are more willing to apply a passive cooling system than traditional cooling system, which has significant potential to reduce traditional energy consumption. There are different types of ventilation systems, and natural cross ventilation is very common in some newly designed buildings. Natural cross ventilation is an open activity that allows air to enter and exit though a building space. In a high temperature climatic zone, this natural cross ventilation system increases the air exchange to reduce the internal temperature.

As can be seen in Figure 3, consideration about the types of openings is necessary. Different degrees of opening and patterns allow the wind to enter differently. A well-designed pattern can help to enhance wind speed, and as a result increase the ventilation rate. A properly designed and accurately positioned shading device can block unwanted solar heat, while increasing wind speed to help cool down interior space, which also has the possibility of enabling the wind to reach deeper into the building for further air exchange. By changing either the shape of opening or the pattern (or both), it is possible to change the wind direction and control the wind more optimally. Differences in sill height can also directly influence wind speed in natural ventilation.[21] Finding the right balance between opening and shading for each project is worth far more attention for its vast passive potential.

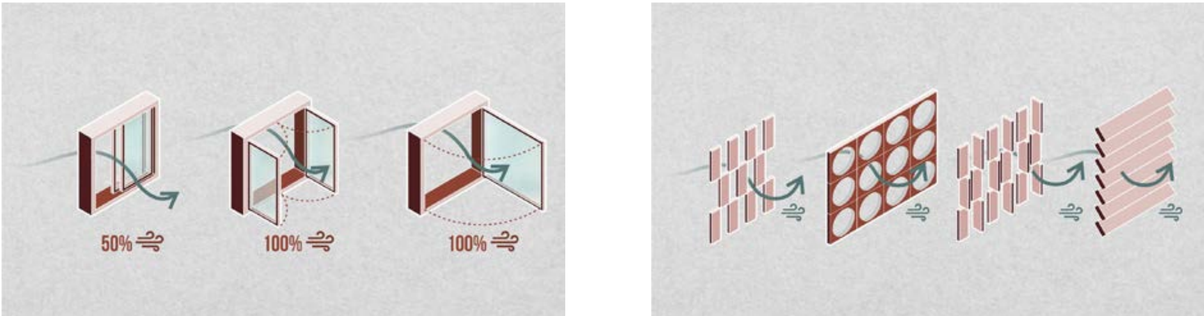


Figure 3 Opening Percentage and Opening Pattern

[21] https://www.archdaily.com/887460/cross-ventilation-the-chimney-effect-and-other-concepts-of-natural-ventilation

III. Theory and Methods

In order to visualize the existing situation of industrial buildings in China, a warehouse in Shanghai was selected as the research object. This warehouse was built over fifteen years ago and is currently managed by Shanghai PVG airport. The warehouse is divided into two parts: warehouse-bulk space and office space. The warehouse-bulk space operates 24-hours a day, 7-days a week, while the office space only operates from 8:00 am to 6:00 pm 7-days a week. A three-dimensional (3D) model was generated in Rhino™, and data analysis was conducted using Grasshopper™ corporate with Ladybug tools, which have a date analytical function.

The reasons for selecting this warehouse were because of building information and utility data, which could be easily accessed from the management company. All further design tests and analysis were created based on existing 3D modeling. This paper studies and tests two simple, passive strategies separately (daylighting and passive cooling), aiming to reduce energy consumption for factory buildings, whilst improving the working environment.

It is difficult to separate building design elements into individual parts when an architect is designing or renovating a building. Each member of the building team can affect each other directly or indirectly. In the same way, when conducting an energy analysis to help achieve better design results, every factor that can affect the analysis should be considered comprehensively. However, there is always a sequential order, where one design issue requires attention before another. Nevertheless, if solving the urgent issue actually makes other issues worse, then it is questionable whether the solution strategy is worthwhile.

Here are the definition of two passive strategies that is studied and tested in this paper.

a) Daylighting allows the maximal use of natural daylight to reduce the energy usage by artificial illumination.
b) Passive cooling reduces the energy used in cooling by preventing the building from overheating.

1. Strategy I: Daylighting

The warehouse selected for this study is considered as one building space when calculating daylighting analysis, although a multiple functional space should be separated into different zones when calculating the cooling load. Simplifying the process of cooling load calculation is necessary in this section. It should be noted here that a general cooling load result is generated at the end by applying warehouse-bulk space working schedule, which is the same schedule applied for the illumination load. The cooling load results are not comprehensive, due to a lack of precision. However, the analysis can still compare the difference between the existing and new cooling loads.

This section provides a design solution to increase the total fenestration percentage, which includes new, open fenestration on the west side of the building, and locating the fenestration at the correct position to allow more daylight into the interior space. Shading devices might be also needed. The expected result of applying the daylighting strategy is that over 55% of regularly occupied floor area will receive ideal daylighting, as specified in Leadership in Energy and Environmental Design, Building Operations and Management (LEED O+M): *Existing Buildings V4 Standard of Daylight Option 1*. By receiving more daylighting, the amount of energy required for illumination can be reduced. Meanwhile, the cooling load might be increased due to the total increase of window to wall ratio.

Three factors are collated by computer software in this daylighting strategy section, which explain the existing daylighting analysis associated with the existing monthly cooling load. These three factors will also be used to generate new daylighting analysis, to determine if the daylighting passive strategy works.

1. How much acceptable daylighting is received across the entire floor area throughout one whole year (%)
2. Monthly (average) energy usage for illumination though out the whole year (kWh)

3. General monthly cooling load (kWh)

At the end of each analysis of passive strategy I, a chart illustrates the percentage of the entire floor area (%), energy for illumination (kWh), and cooling load (kWh), with new design analysis data summarizing and visualizing the final results. No comparison is required between these three factors because each has their own variables and calculation. The only comparisons occur between existing building results and new design results. The final results help to determine if the design solutions work, and how much improvement is generated by this passive design solution.

2. Strategy II: Passive cooling

In this section, the selected warehouse has to be separated into five different zones (explained in chapter IV) to run the cooling load analysis. The reason why cooling load should be calculated according to different zones is because separate controllers are required for automatic adjustment. The regional building HVAC system will continue to turn on when the building is occupied during the hot season.

There are three steps to the passive solutions approach for cooling energy reduction. The first step requires a reduction in total solar heat gain by adding appropriate shading devices. The second step is to reduce the energy consumption by resetting a suitable HVAC operation schedule. The new HVAC operation schedule is based on building type, occupancy schedule, number of people per area, and different occupancy activity level. The third step requires an appropriate timing for open fenestration to be found to cool the interior by air exchange.

Applying passive cooling is expected to result in a reduction of over 20% of the cooling load for each zone. Applying natural ventilation successfully will also attain the prerequisite credits of minimum indoor air quality performance of LEED O+M: Existing building V4). Meanwhile, energy for illumination might be affected as a result of the changing of fenestration. A new percentage of regular occupancy is generated for the whole area receiving suitable daylighting to determine a comprehensible result.

Three factors are collated by computer software in this passive cooling strategy section to explain the existing cooling energy consumption associated with existing daylighting analysis. These three factors are also used to generate new cooling analysis to determine if the passive cooling strategy works.

1. Monthly solar heat gain (kWh)
2. Monthly (average) energy usage for cooling space (kWh)

3. How much acceptable daylighting is received across the entire floor area throughout one whole year (%)

At the end of each analysis of strategy II, a chart presents solar heat gain (kWh) for each zone, energy for cooling (kWh), and the percentage of the entire floor area (%) for existing analysis data and new design analysis data, to summarize and visualize the final results. No comparison is required between these three factors because each of them has their own variables and calculation. The only comparisons occur between existing building zone data and new design data. The final results help to determine if the design solutions work, and how much improvement is generated by the design solutions. Here it is worth noting that the building will still be considered as one entire space when calculating daylighting per floor area.

IV. Analysis

This analysis section is divided into three parts: the first describes the building information, the second explains the climate of Shanghai, and the third presents the energy analysis of the subject warehouse, which includes daylighting analysis, cooling load analysis, and illumination load, and solar heat gain.

1. Existing building information

Figure 4 through to Figure 7 provide the floor plan, elevation, and 3D perspective view of the selected warehouse. The shape of the warehouse is a simple rectangular box, with a flat roof. The exterior wall is built from non-insulated concrete, while the roof is built from non-insulated metal trusses. The south side of the warehouse is the same as the north side. The large openings are the loading docks while the small openings are windows. The loading docks are closed at regular times, and are only opened when loading activity happens. The west side of the building is total enclosed, with no opening located on the existing west side wall. Figure 5 and Figure 6 indicate the size of the windows and loading docks. The entire window-to-wall ratio of this warehouse is approximately 6.4%. There are five individual spaces separated by interior walls, each managed by individual owners (see Figure 7). The existing lighting system and HVAC are both operated automatically. The analysis mainly focuses on Zones A, Zone C, and Zone E when conducting the cooling analysis. Zone C was chosen instead of Zone B or Zone D is because of being located in the middle of the warehouse building, the results are more universal.

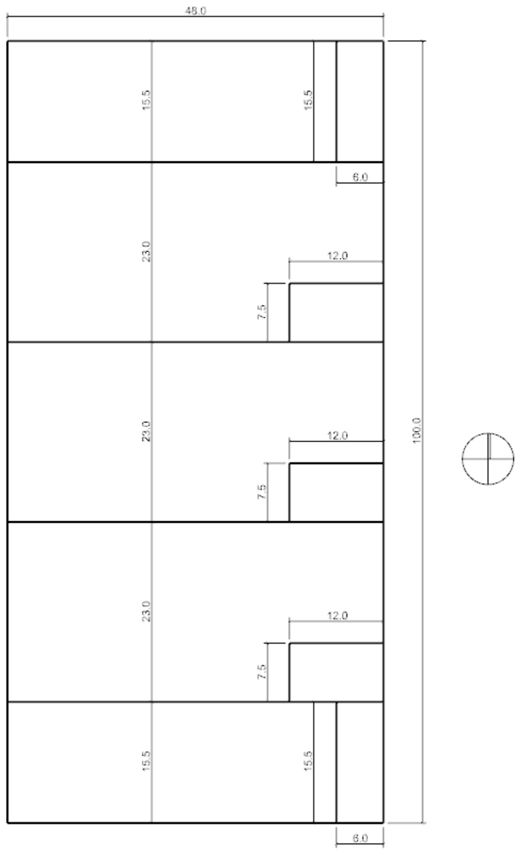


Figure 4 Floor plan

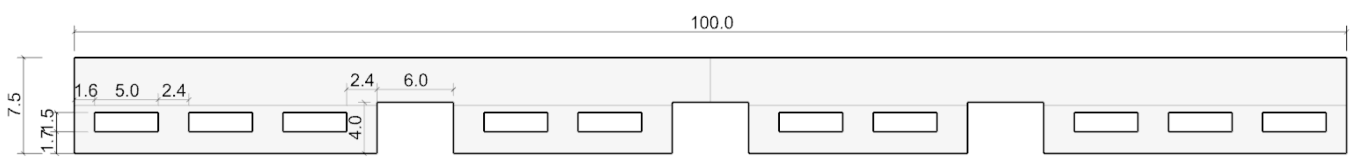


Figure 5 East of warehouse

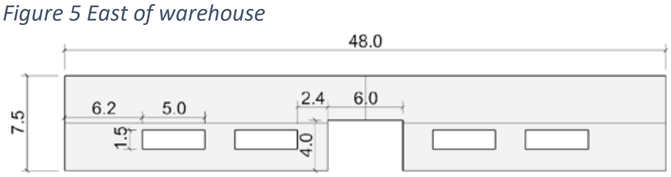


Figure 6 South of warehouse

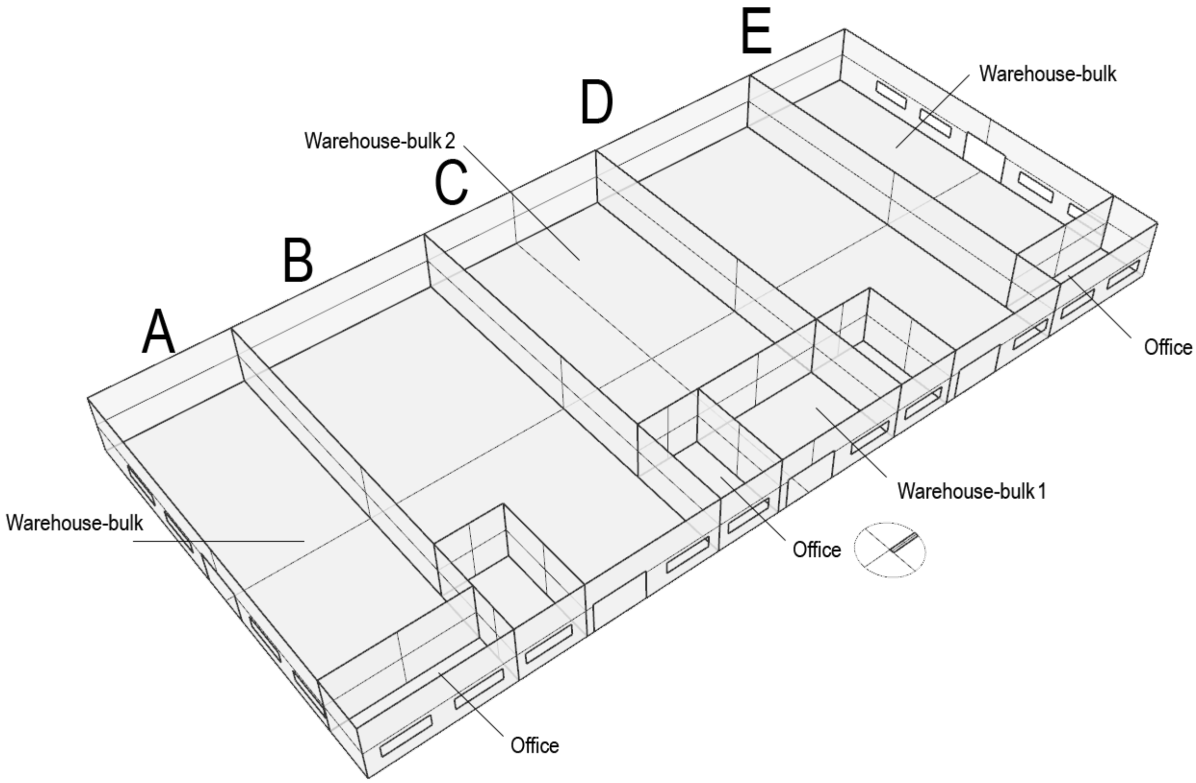


Figure 7 Warehouse Perspective View

2. Local Climate Analysis and conclusion

According to weather reports, the highest temperature recorded in Shanghai in 2017 was 40.9 ℃. All weather data is collected by the International Weather for Energy Calculations (IWEC). In Figure 8 , a whole year dry-bulb temperature (℃) analysis of Shanghai is presented, whilst Figure 9 presents the relative humidity (%) analysis for the whole year. According to ASHRAE standard 55, most people feel comfortable if the temperature is between 20 to 22 °C, with a 30-60% humidity level[22]. The comfort zone is labeled on the right side of Figure 8 and Figure 9. In Figure 8 , the highest temperature is marked as red and the lowest temperature is marked as blue. In Figure 9 , the highest humidity level is marked as red and the lowest humidity level is marked as blue.

It is evident that Shanghai suffers from a high relative humidity ratio throughout the year. The highest temperature appears at the middle of a day when the sun rises to the highest angle. Mapping these two charts, the temperature gap from late June to early July is the rainy season of Shanghai. During this period, the average temperature drops to 20 °C. The heavy precipitation helps to cool the dry-bulb temperature, while at the same time the relative humidity reaches a peak. Thermal comfort is both directly and indirectly related to humidity effects.[23] The human body cools by evaporation, a process known as perspiration. As the relative humidity ratio increases, the evaporation of perspiration slows down, and the human body starts to feel uncomfortable because the body heat release rate slows down as well. This effect is especially obvious during hot seasons.

These analysis charts indicate that only a short period of Shanghai is under comfortable temperature and acceptable humidity levels through a whole year. If high humidity is the only

[22] Standard, A. S. H. R. A. E. "Standard 55-2004." Thermal environmental conditions for human occupancy (2004): 9-11.
[23] Berglund, Larry G. "Comfort and humidity." ASHRAE journal 40, no. 8 (1998): 35.

reason for discomfort, it is possible to maintain the situation, however when the temperature is also high it becomes difficult to continue. Imaging the building situation of exercise gym, it is evident that people can bare high humidity when the temperature is lower. Therefore, the problem of high temperatures is more serious, while high humidity is less of a concern in this particular study.

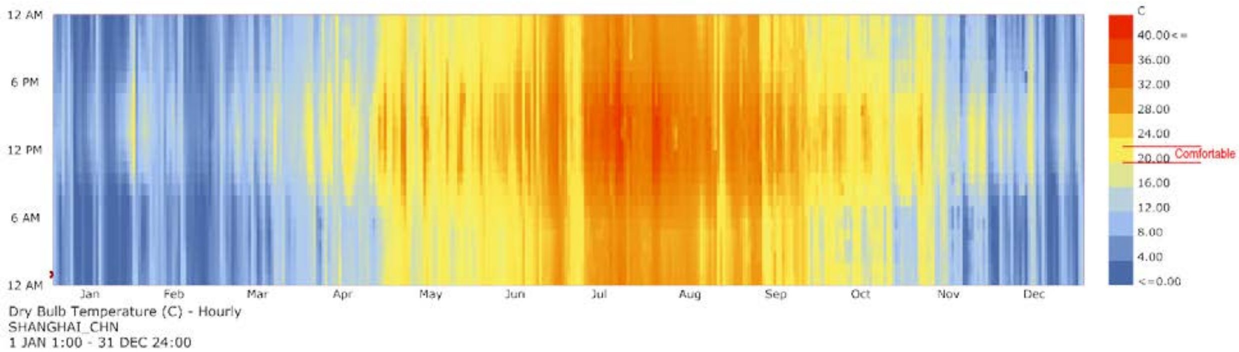


Figure 8 Dry Bulb Temperature: Small amount of time is in comfort area

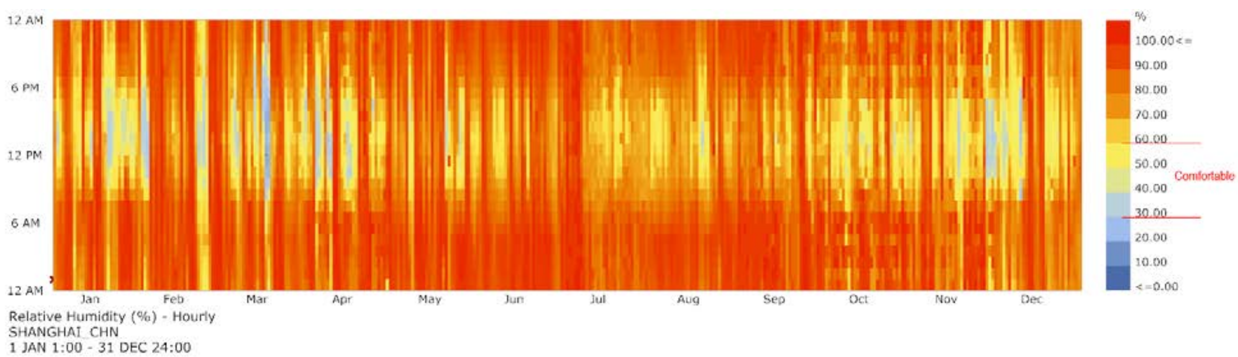


Figure 9 Relative Humidity: Small amount of time is in comfort area

A person’s metabolic rate and clothing level is required to generate a psychrometric chart. According to ASHRAE55, "A person’s metabolic rate will be 1.8 met if he spends 30 minutes out of each hour lifting/packing, 15 minutes filing, 15 minutes standing, and 15 minutes walking around.” [24] Therefore, the metabolic rate of the workforce who are working in the selected warehouse-bulk area is assumed to be 1.8. In summer time, people usually wear T-shirts

[24] American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE Standard: Thermal Environmental Conditions for Human Occupancy. ASHRAE, 2010.

with a clothing level of 0.5. (Level 1 refers to a 3-piece suit in an office space, while heavy winter jackets would have a clothing level of 2 to 4). It is assumed that workers will take off their jackets when doing heavy-duty work. Therefore, the average clothing level of workers during the entire year is about 0.75. A person’s metabolic rate is 1.1 met while seated and typing in an office space, and the clothing level is 1.

Figure 10 presents the psychrometric analysis of workers in the warehouse-bulk area, and the possible improvements after applying a passive strategy. As highlighted in part "a", the analysis indicates that only 26.1% of the entire year provides a comfortable environment for workers. Part "b" indicates that 10.4% of the time can be added to the comfort zone by applying thermal mass and a night time ventilation strategy. Part "c" indicates that 7.3% of the time can be added to the comfort zone by applying an evaporative cooling strategy. Finally, part "d" indicates that 9.8% of the time can be added to the comfort zone if the occupants use fans appropriately. Further, results suggest that dehumidification and internal heat gain do not improve the comfort zone.

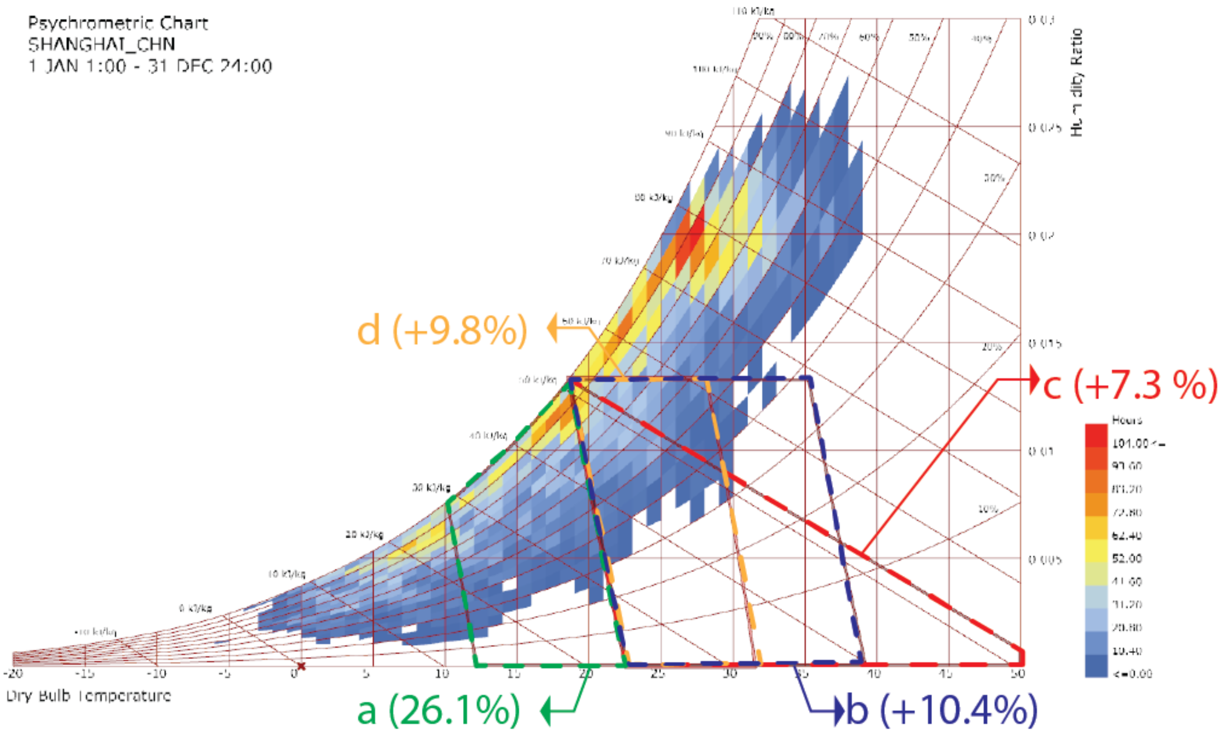


Figure 10 Psychrometric Chart of labors in warehouse-bulk space

Figure 11 presents the psychrometric analysis of office staff, and the possible improvements after applying a passive strategy. First, part "A" indicates that only 23% of the entire year provides a comfortable environment for office staff to work. Part "B" shows that 6.8% of time can be added to the comfort zone by applying a thermal mass and night time ventilation strategy. It is clear from part "C" that 4.9% of time can be added to the comfort zone by applying an evaporative cooling strategy. Part "D" shows that 5.8% of time can be added to the comfort zone if the occupants use fans appropriately. Finally, part "E" indicates that 12.6% of time can be added to the comfort zone by applying an internal heat gain strategy. Results also indicate that dehumidification does not offer any improvement to comfort zone.

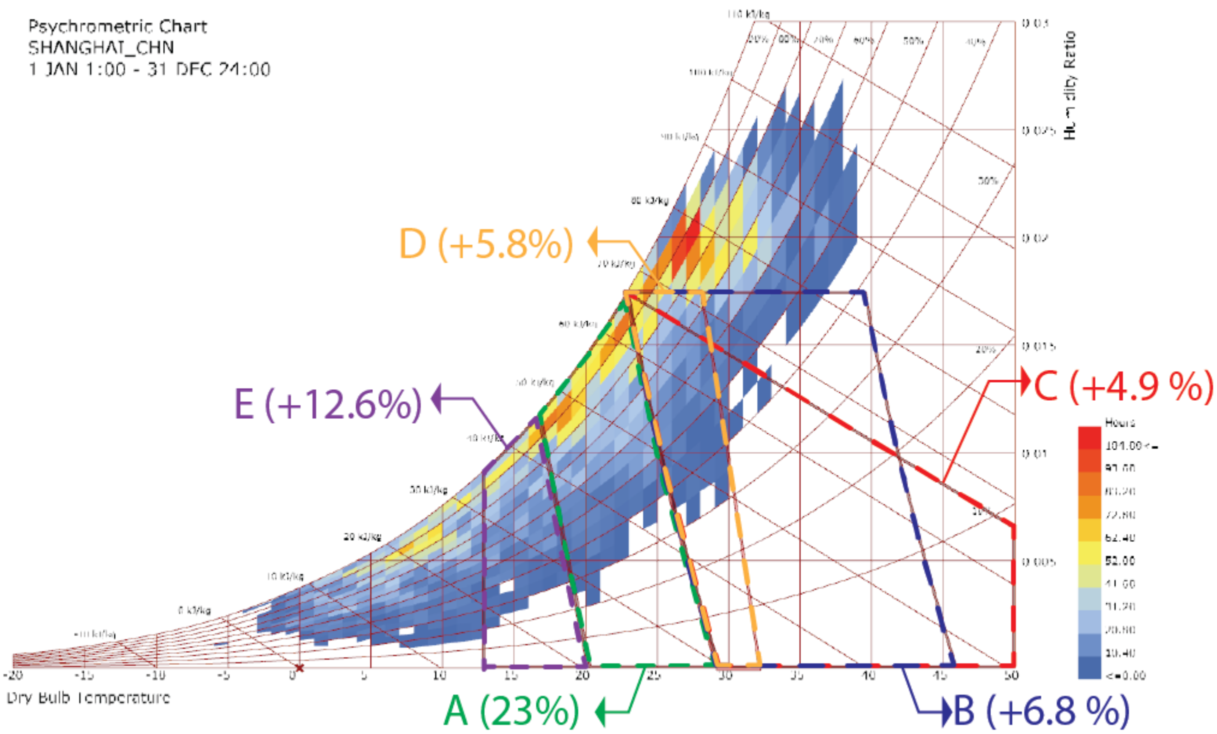


Figure 11 Psychrometric Chart of office staffs of office space

Internal heat gain works better for a small-scale building with a well-insulated building envelope, however the building in this study is an existing large-scale warehouse building without such a feature. When renovating an existing building, less demolition is always desirable. As a result, the internal heat gain strategy is not applicable to this study object because it is impossible to rebuild the entire building envelope. A thermal mass and night time ventilation strategy provide the best results compared to the other passive strategies, which could be understood as operating natural ventilation during the night, to exchange the heat inside the corporate building with effective thermal mass to control the solar heat gain during the day.

There are many reasons why the amount of sunlight admitted into a building should be controlled, one of which is improving the quality of interior illumination by controlling natural daylight. Another is to block solar heat to reduce high cooling energy consumption in the hot season. A well-designed shading device can also improve the user's visual comfort by controlling glare.[25] A shading device should definitely be applied to this building; this is the easiest method of avoiding direct solar heat gain.

Adequate ventilation at night, (known as night purge ventilation, or "night flushing") can help to release the heat energy accumulated during the day. This passive strategy is useful when the air temperature is too high in the daytime. Especially in this case, Shanghai suffers a high temperature during summer time, while the operation period of this warehouse is 24-hours a day. Night flushing can be extremely helpful for reducing the cooling load at night when the warehouse is still being occupied by workers with regular working activity.

There are two major reasons why people want windows to be open. First, to exchange the interior air to gain sufficient oxygen volume. Second, to bring outside, cooler air into the interior

[25] https://www.wbdg.org/resources/sun-control-and-shading-devices

space to help release the interior heat when the outdoor temperature is lower. How this action affects building energy consumption can be measured by the change in the amount of cooling load. In response to the need for conditional statements, wind rose analysis would be required to identify the potential location of fenestration and the potential timings for windows to be opened. In other words, such a wind study helps to establish effective timings for the operation of the windows for air exchange, with a suitable air temperature and wind speed.

According to the ASHRAE 55 Standard, and as shown in Figure 12, "an increase in airspeed of 0.8 m/s can help to cool down 3 °C air temperature if the air temperatures are 5 °C (41 °F) lower than the radiant temperatures. When the air temperatures are 5 °C (°F) higher than radiant temperature, a 1.6 m/s (3.6 mph) airspeed increase is required."[26] Thus, increasing air movement has the potential to also reduce cooling load.

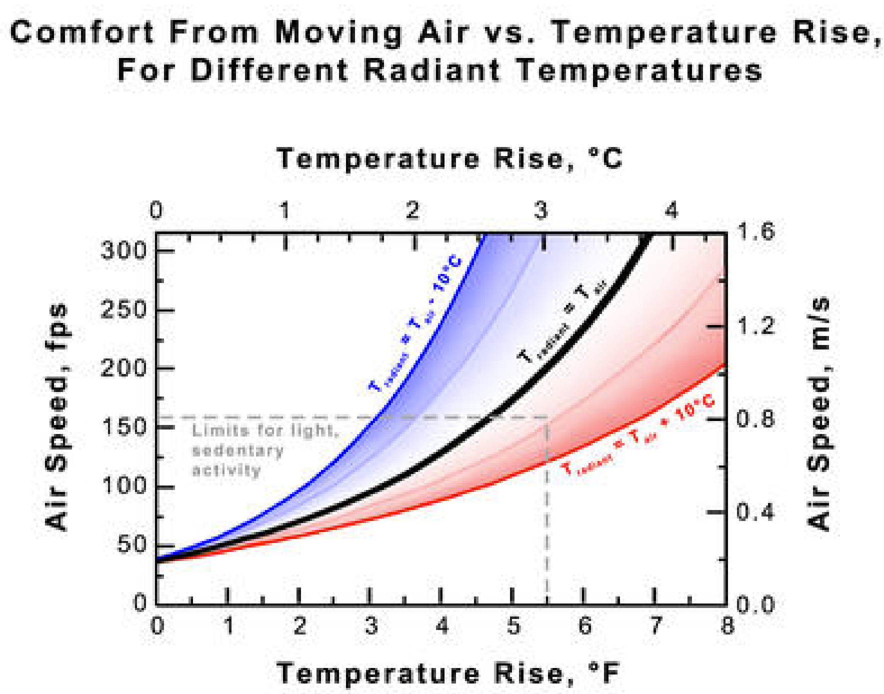


Figure 12 Air speed vs Temperature Rise

[26] Standard, A. S. H. R. A. E. "Standard 55-2004." Thermal environmental conditions for human occupancy (2004): 9-11.

As mentioned previously, the metabolic rate of a worker (working in the warehouse bulk space) is around 1.8, which is higher than a regular office worker. Therefore, for the warehouse workers, the acceptable wind speed could be higher than in the regular office space while the acceptable air temperature could be lower due to a higher metabolic rate. Indoor air speed over 1.6 m/s is completely acceptable. In this wind study, only results from the hot season will be used for future analysis because in the cold season windows tend not to be opened. Further analysis is based on the hypothesis that the ideal condition is to have wind speed greater than 1 m/s and an air temperature lower than 26 ℃, as illustrated in Figure 13 through to Figure 16.

The spring season of Shanghai is from March 1st to May 31st. The summer season is from June 1st to August 31st. The fall season is from September 1st to November 30th. The winter season is from December 1st to February 28th.

The following wind charts illustrate the potential for natural ventilation. The size of the polyline area indicates amount of the wind with desirable air temperature and wind speed. The direction of the polyline area indicates the wind direction.

24.66 % in total of qualified wind comes from east side and south side during spring season, which is a good sign for applying natural ventilation. Only 9.98 % in total of the wind comes from east side of the building while most of the wind air temperature in summer season is higher than is 26 °C. 22.52% in total of qualified wind comes from south side of the wind, which is also good to know for further potential of using natural ventilation. 24.66% of qualified wind comes from west side of the building during the winter season.

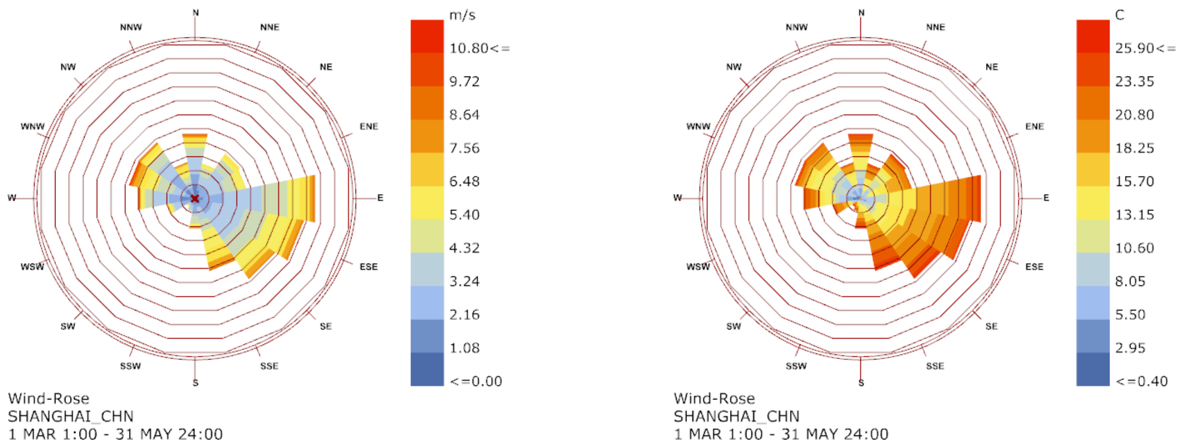


Figure 13 Spring Wind Rose

As can be seen, the spring season has greater potential to use natural ventilation compared to the summer time when the air temperature is too high to use.

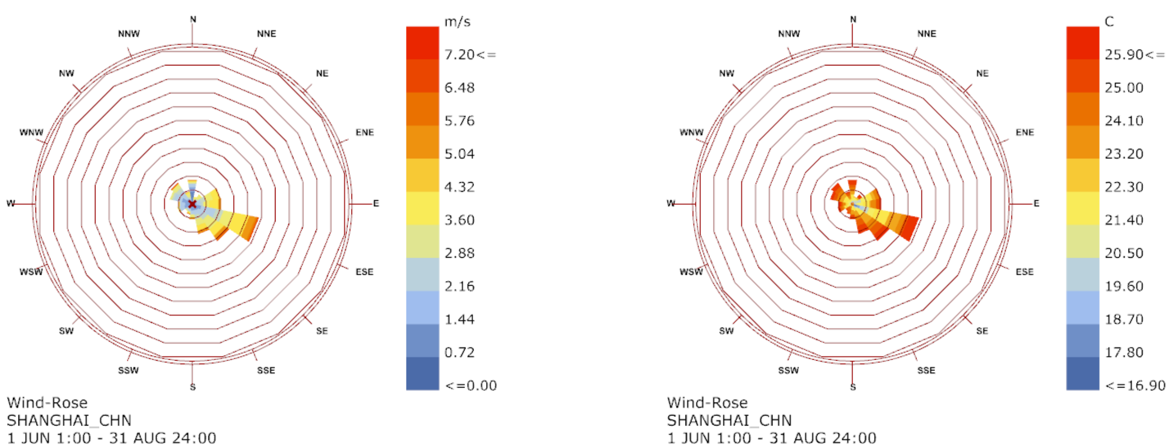


Figure 14 Summer Wind Rose

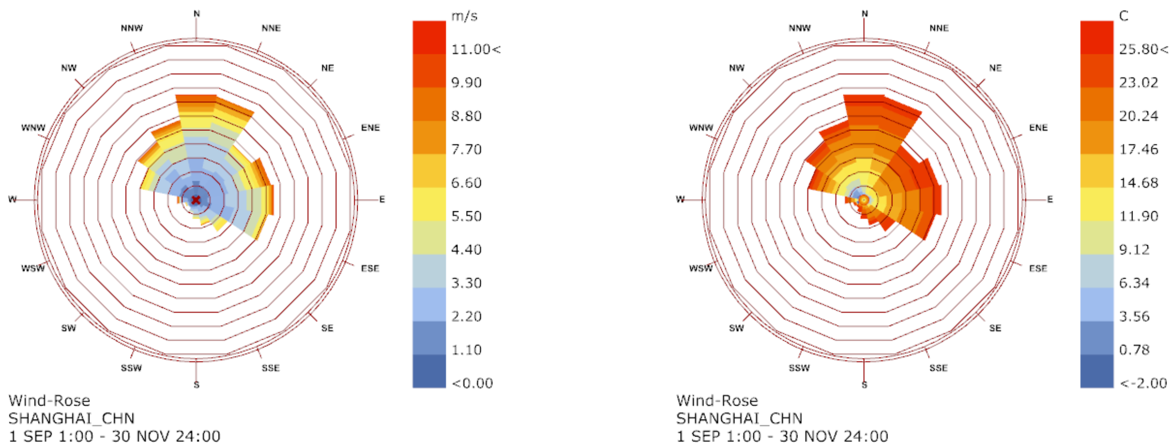


Figure 15 Fall Wind Rose

As can be seen, the fall season has greater potential to use natural ventilation as well compared to the winter time when people usually do not open the windows.

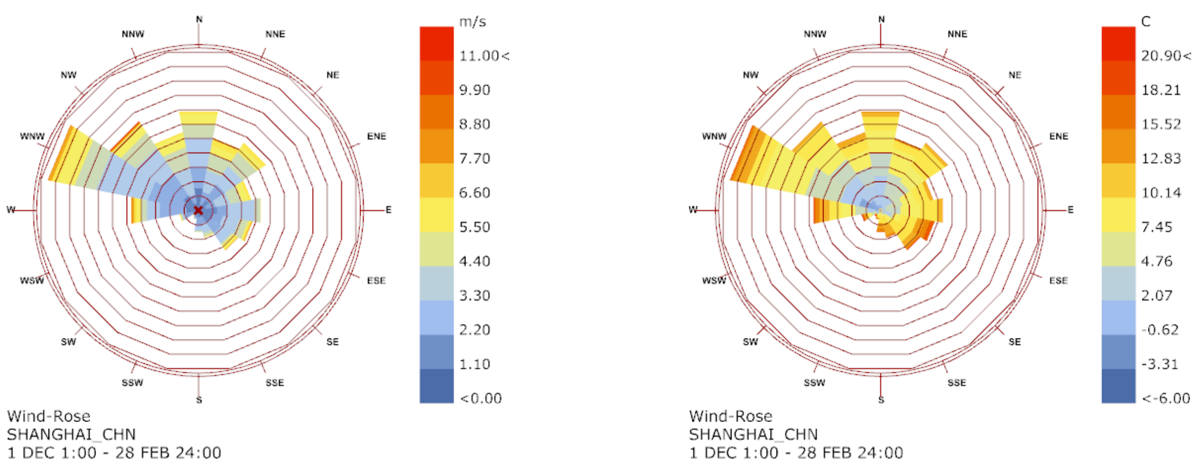


Figure 16 Winter Wind Rose

Wind study results shows that most of the desired wind (with ideal temperature and wind speed) comes from either the east or the north. The regional window location is suitable to apply natural ventilation. Thus, no fenestration change is required for further cooling load study in the passive cooling strategy section.

3.1 Existing buildings energy usage (When solving lighting issues is primary)

Lighting and cooling devices drive the majority of electricity consumption of a building. In the following section, existing lighting analysis, illumination load and cooling load analysis are included. All information required to build a 3D model and to run the data are set as close as possible to real conditions. Any possible energy leak due to building materials will not be discussed in this paper.

The first energy analysis section gives primacy to daylighting data, supplemented with electricity load for illumination and interior temperature.

A. Existing buildings energy usage

1. Daylighting Analysis

Currently, the warehouse possesses several design weaknesses. Lacking natural daylighting is the first serious issues of this building.

Figure 17 Exterior facade of Warehouse

Figure 18 Interior space of Warehouse

Once the loading dock (dimensions 6 × 4 m) is closed, the windows on the east, south, and north sides of the building —as shown in Figure 17—are the only channels for natural light to reach the interior space. The artificial lights in the warehouse-bulk space (as shown in Figure 18) are too dim and dangerous for a working area. The visibility inside the warehouse is very poor, even when the loading dock doors are kept opened during busy hours. The existing window is only 1.5 x 5.0 m in size. The window-to-wall ratio on the east side is 0.11; the south side ratio is 0.90, and the north side ratio is also 0.9. There is no window on the west side of the warehouse. The opening percentage is very low, and some of the windows are even blocked by office furniture placed against the windows. As a result, the illumination of existing warehouse-bulk space could only rely on the dimming artificial lights, and one fenestration on the east side of the building. Study shows "20 to 50 foot candle is sufficient for warehouse activity, while it requires 100 foot candle for office activity."[27] The illumination range from 100 lux (10 foot candle) to 2000 lux (200 candle) is desirable in this study object, Based on this statement, a daylighting analysis has been created and the results are presented in Figure 19.

There are a total of 2143 test points in this daylighting analysis. The text point level setting is 0.75 m, which is the height of working plane level. The left part of the figure presents the regular daylighting analysis by the lux level. Using computer calculation, every point illuminated between 100 and 2000 lux is marked as red, which is considered true. The right-side of the figure shows the percentage of floor area that receives proper daylighting (where 1 means true which is marked as red and 0 means false which is marked as blue). Spring equinox is chosen to generate climate-based sky data according to data universality.

Considering the entire warehouse as one building area, only 11.2% of the warehouse space received appropriate daylighting illumination, and most of this lighted area is in office space. The red area is a very small area of the total space, and the most illuminated area is office space. The majority of the warehouse-bulk space hardly has access to daylighting, where the laborers are handling some high-risk work. This analysis further explains lacking natural light is a major problem in industrial buildings in China.

[27] Tinker, Miles A. "Illumination standards." *American Journal of Public Health and the Nations Health* 36, no. 9 (1946): 963-973.

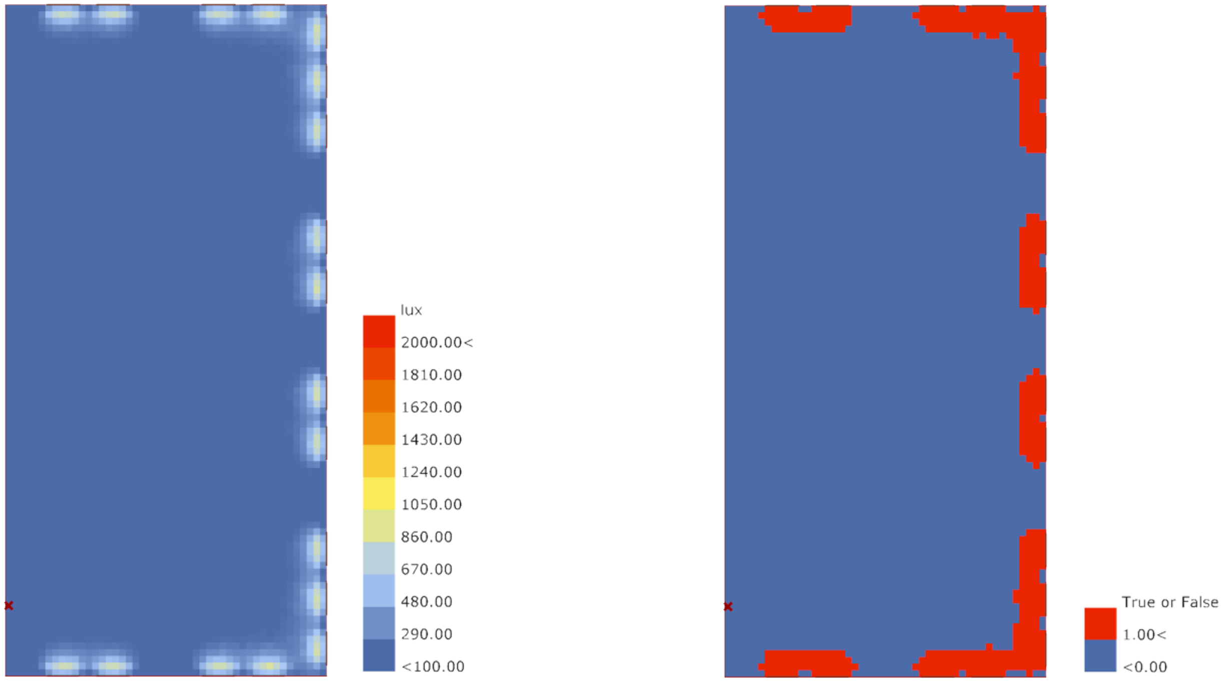


Figure 19 Daylighting analysis

2. Illumination load

In order to simplify the analysis process of illumination consumption, the warehouse is considered as one functional space. The warehouse-bulk space operating schedule is applied to generate illumination data, although the operation schedules for warehouse-bulk space and office space are different. The applied operation schedule operates 24-hours a day, 7-days a week, and the lighting fixtures are always turned on when the building space is occupied, according to the information provided by the management company. The left side of the chart indicates the time range of the analysis (from 12 am through to 12 am). The right side of the chart indicates the illumination load, which is from low to high. Along the x-axis of the chart the twelve months of the year are displayed. From 12 am to 1 pm is lunchtime, when only 20% of lighting fixtures are turned on for those workers who do not take a lunch break. Figure 20 and Table 1 present the selected warehouse interior lighting load. Expect for the lunch time at 12 pm, the lighting fixtures are fully operated, holding a peak illumination load.

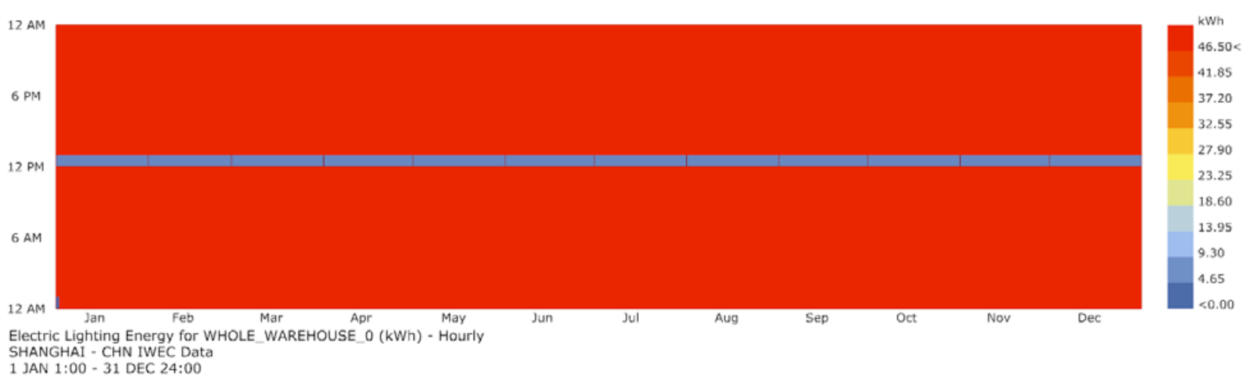


Figure 20 Monthly E/L

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
KWh	33216	30038	33266	32173	33257	32195	33250	33243	32185	33239	32174	33244

Table 1 Monthly E/L

3. Cooling Load

The warehouse-bulk space working schedule is applied to generate the general cooling load of the entire warehouse space, as presented in Figure 21 with monthly data presented in Table 2. The left side of the chart indicates the time range of the analysis from 12am to 12 am. The right side of the chart indicates the cooling load range, which is from low (blue) to high (red). The x-axis of the chart presents the twelve months of the year. Between April and October is the hottest period of the year, when cooling is required. As the results show, from later June to early September is the hottest time during the year, and between 12 and 6 pm is the hottest time during the day, which has the highest cooling load. The annul peak cooling load is 342 kWh.

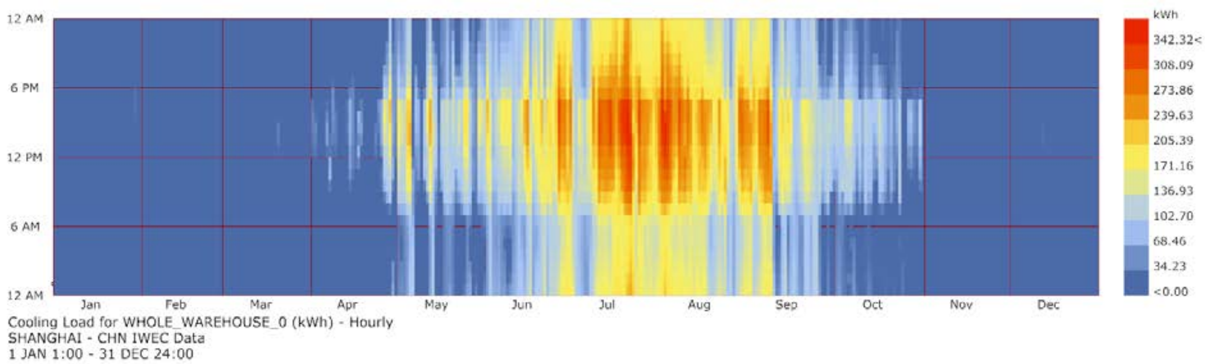


Figure 21 Cooling load of whole warehouse space (Existing)

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	7872	42475	86603	130650	127073	75424	23464	5049	0

Table 2 Cooling load of whole warehouse space (Existing)

4. Conclusion of existing building annual energy (When daylighting is primary)

A total 11.2% of regularly occupied area receives acceptable daylighting, between 100 and 2000 lux. The average electricity consumption for illumination is 32623 kWh , and the average electricity consumption for space cooling from April to October is 70508 kWh.

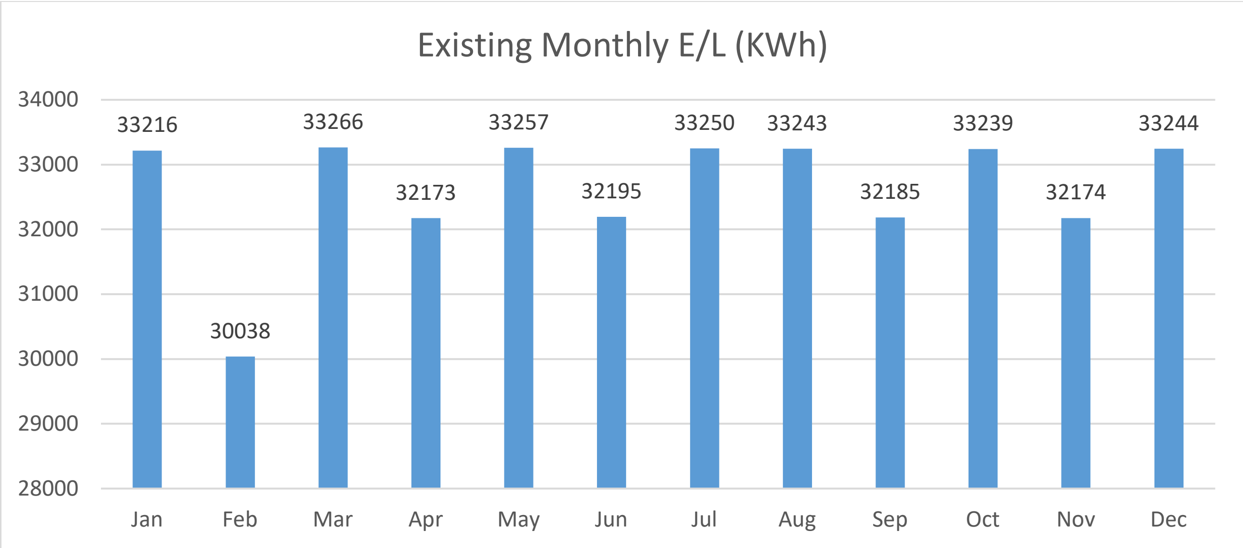


Figure 22 Existing Building Electricity Consumption for illumination (KWh)

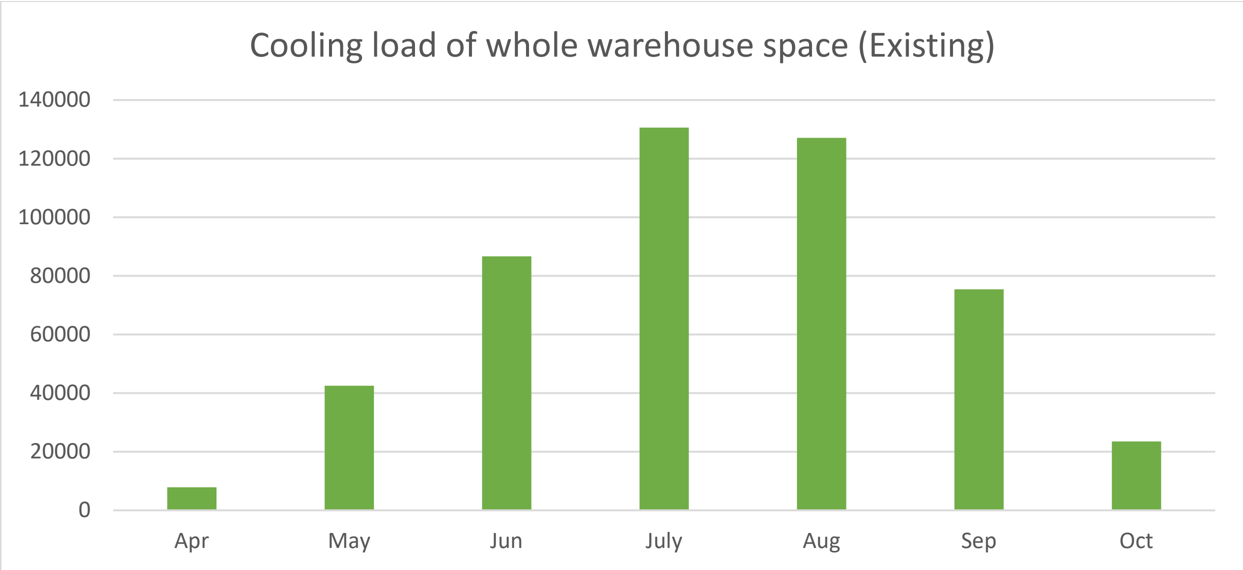


Figure 23 Existing Monthly cooling load (kWh)

3.2 Existing buildings energy usage (When solving cooling load issues is primary)

It should be noted that the second energy analysis gives primacy to cooling load, supplemented by interior temperature and the percentage of entire floor area achieving appropriate daylighting. The warehouse will be divided into five different zones when calculating the cooling load analysis. The office space operation schedule runs from 8 am to 4 pm each week. Warehouse-bulk space operates 24-hours a day, 7-days a week. According to the management company, the cooling temperature is 22 °C constantly for office space during the hot season, and 18 °C for the bulk space. Only Zone A, Zone C and Zone E is selected to generate the analysis data.

B. Existing buildings energy usage

As shown in the cooling analysis charts, the left side of the chart indicates the time range of the analysis. The right side of the chart indicates the cooling load range, from low (blue) to high (red). The x-axis presents the twelve months of the year.

For the solar heat gain charts, the left side of the chart indicates the time range of the analysis, whilst the right side of the chart indicates the solar heat gain, from low (blue) to high (red). The twelve months of a year are presented along the x-axis.

For each office space, the highest cooling load appears in 7 am which is the time when space is starting to be occupied. It requires more energy to operate cooling equipment than maintain the cooling temperature at a certain cooling point. The highest solar heat gain of office also appears around 7 am because of all office space is facing to the east. The sun rise angle changes in two directions over time in a day. As a result, the daylighting no longer illuminates the office space from east through the window, as part of the solar heat is blocked by the building.

For each bulk space, the operation schedule is 24-hours a day, 7-days a week. The highest cooling load appears at the middle of a day when the sun rise to its height angle and holding a highest heat energy. It cost more energy to lower a cooling point than maintain the cooling temperature at a certain cooling point.

The solar heat gain of each warehouse bulk space are different due to a different orientations. Result details will be explained in the individual in the following analysis section.

1. Zone A Area

1.1 Warehouse - Zone A - Office space cooling load

The cooling load for the Zone A office space, as shown in Figure 24 and Table 3 indicates that the highest cooling loading according to the analysis is 26.21 kWh which appears in 7 am. The cooling period is from April to Oct. Solar heat gain for Zone A office space is presented in Figure 25 and Table 4. The highest solar heat gain is 7.22 kWh around which appears in 7 am as well. This is because of the building space is under directly sun illuminated from east side in this time.

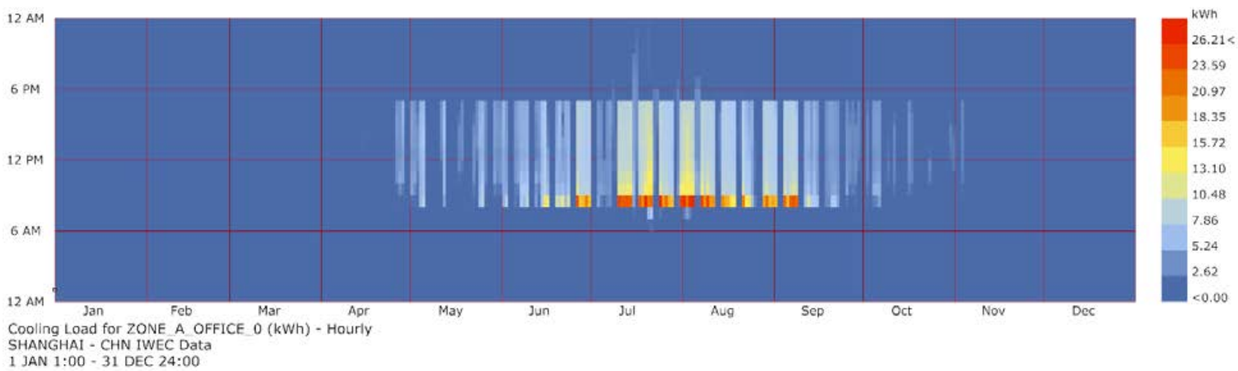


Figure 24 Zone A office space Cooling load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	75	448	1052	1698	1800	900	163	0	0

Table 3 Zone A office space Cooling load

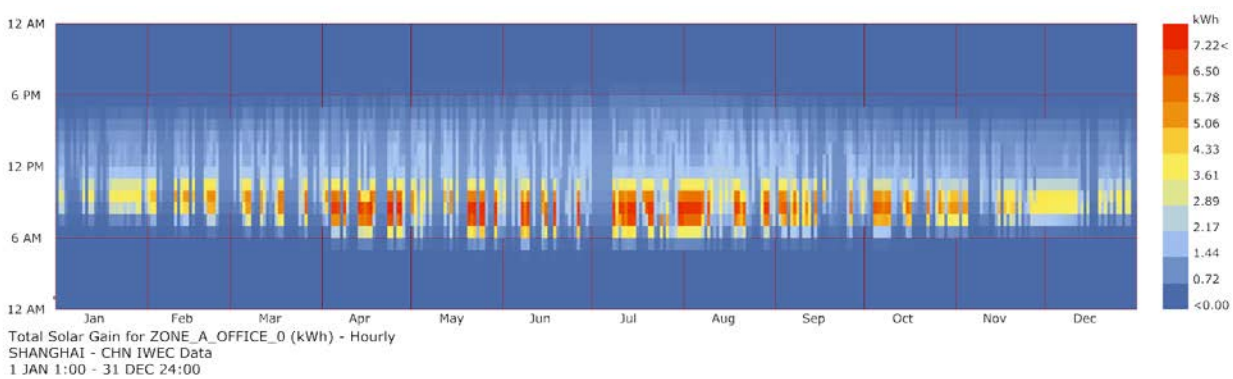


Figure 25 Zone A office space solar heat gain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	301	314	380	583	543	504	658	697	448	481	356	341

Table 4 Zone A office space solar heat gain

1.2 Warehouse - Zone A - warehouse-bulk space cooling load

The cooling load for zone A bulk space is presented in Figure 26 and Table 5. The highest cooling load according to the analysis is 51.60 kWh, which appears at the middle of a day when the sun is holding the highest heat energy. Monthly solar heat gain for zone A bulk space is presented in Figure 27 and Table 6. For bulk space A, the diagram shows an opposite results than others. The bulk space A receives a lower solar heat gain in the hot season, and receives more heat gain in the cold season. This is because of the sun rise angle. Bulk space A is facing to the south. During the hot season, most of the daylighting from south is a high angle daylighting beam. The amount of the sun light is blocked by the building, so the amount of the solar heat is also blocked. During to the cold season, most of the daylighting from south is a lower angle daylighting beam, as a result more sun light beam can come through the windows, so the bulk space A receives more solar heat compare to summer time.

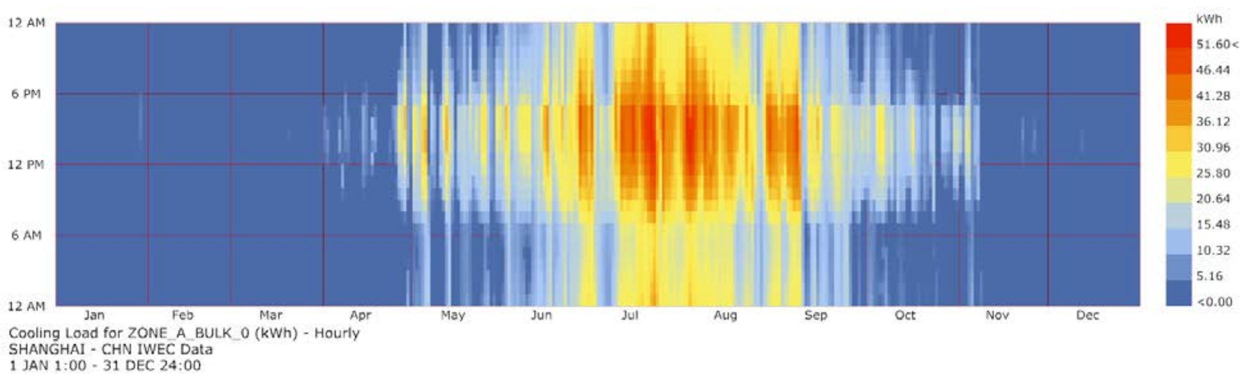


Figure 26 Zone A bulk space Cooling load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	1186	6413	13173	19900	19595	11767	4105	0	0

Table 5 Zone A bulk space cooling load

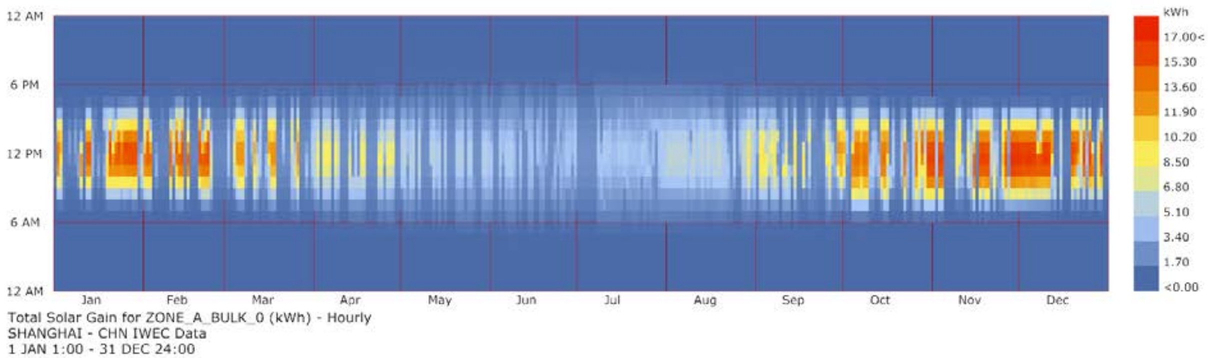


Figure 27 Zone A bulk space solar heat gain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	1339	1111	998	945	792	728	806	1055	985	1598	1563	1769

Table 6 Zone A bulk space solar heat gain

2. Zone C Area

2.1 Warehouse - Zone C - warehouse office space cooling load

The cooling load for zone C office space is presented in Figure 28 and Table 7, which is less than zone A office space, having a smaller floor area and a smaller window size. The highest cooling load according to the analysis is approximately 23.69 kWh, which appears in 7 am. Solar heat gain for zone C bulk space is presented in Figure 29 and Table 8. The highest solar heat gain is 3.61 kWh, which appears in 7 am as well.

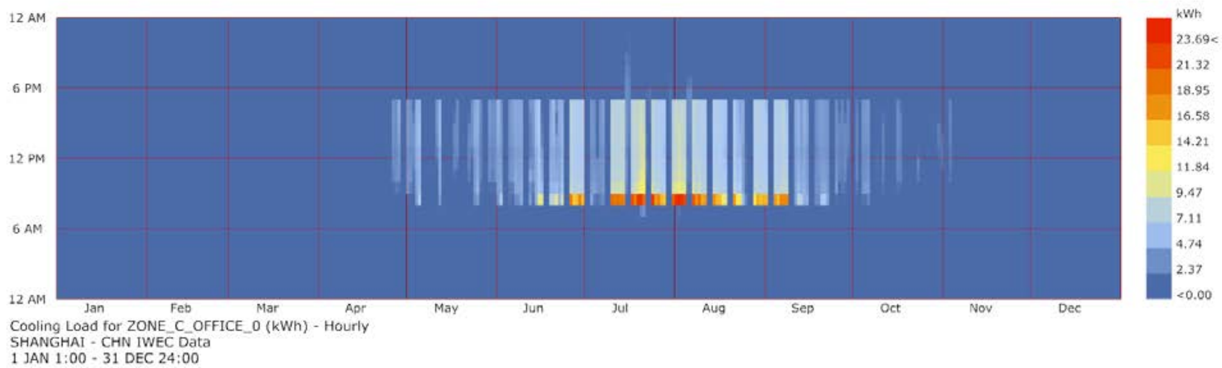


Figure 28 Zone C office space cooling load (Monthly)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	55	344	879	1383	1493	758	123	0	0

Table 7 Zone C office space cooling load

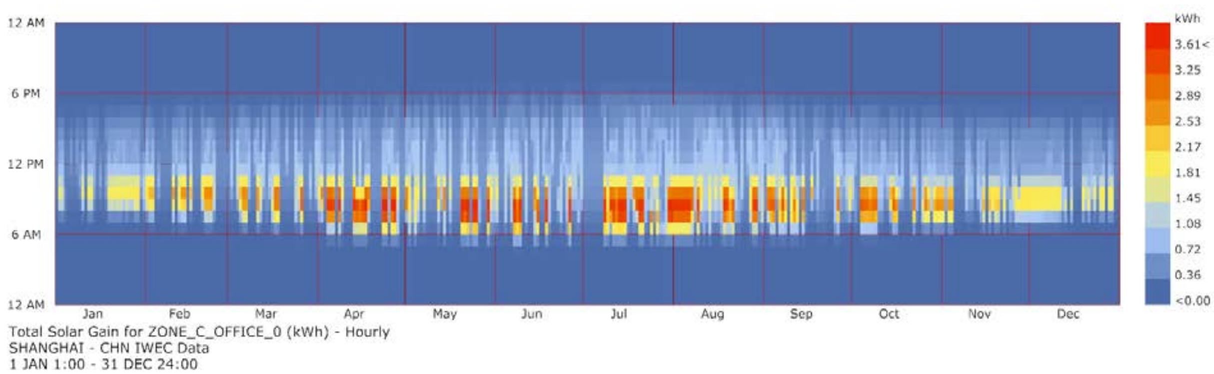


Figure 29 Zone C office space solar heat gain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	152	158	191	293	273	253	331	351	225	242	179	172

Table 8 Zone C office space solar heat gain

2.2 Warehouse - Zone C - warehouse office space cooling load

Zone C warehouse-bulk space is divided into two parts: space 1 and space 2, the results of which are presented in Figure 7. Although spaces 1 and 2 have the same function and are physically treated as one space, the energy analysis has to be conducted separately. A difference in orientation or location can cause different results. The definition of "ZONE" in "Grasshopper-Honeybee" is that each surface of a zone must be able to see every other surface of the zone. If any negative surfaces appear, the generation of the zone (an enclosed space) will fail. As a result, zone C warehouse bulk-space area had to be represented separately as two different zone areas. Zone C bulk space 1 has one window opening, while zone C bulk space 2 has no window opening.

Zone C bulk space 1 with window

Zone C bulk space 1 cooling load is presented in Figure 30 and Table 9. The highest cooling load, according to the analysis, is 15.12 kWh. The monthly solar heat gain is presented in Figure 30 and Table 9. The space 1 has the same design condition as other office spaces by facing to the east. As a result, the highest solar heat gain of bulk space also appears around 7 am.

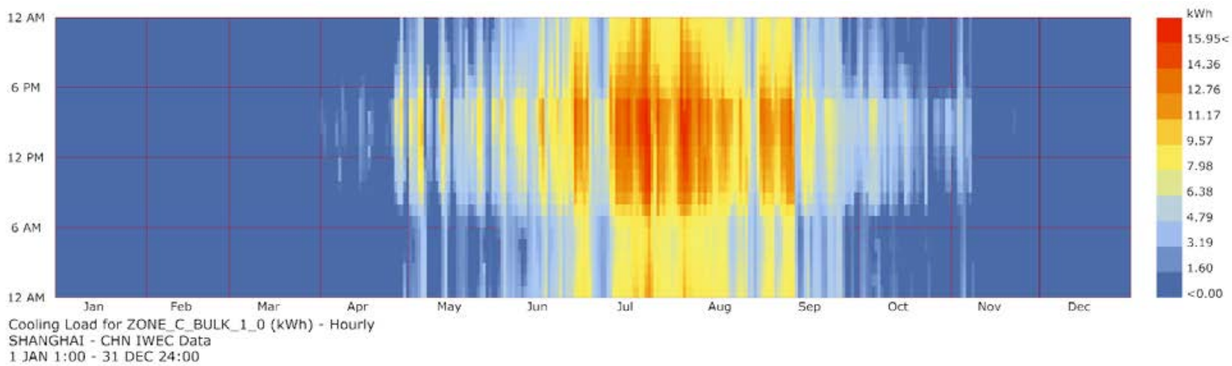


Figure 30 Zone C bulk space 1 cooling load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	343	2030.9	4185	6365	3258	3661	1129	0	0

Table 9 Zone C bulk space 1 cooling load

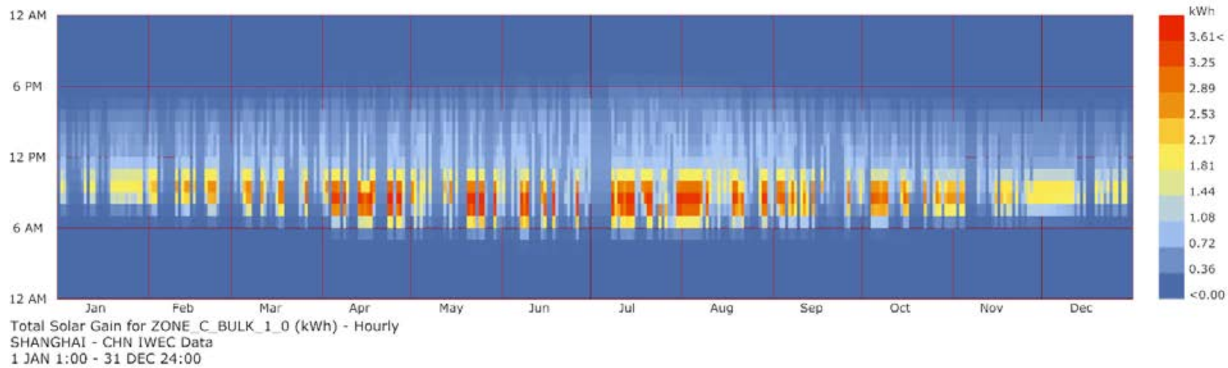


Figure 31 Zone C bulk space 1 solar heat gain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
kWh	150	157	189	291	271	252	329	348	224	240	177	170

Table 10 Zone C bulk space 1 solar heat gain

Zone C bulk space 2 without window

Zone C bulk space 2 cooling load is presented in Figure 32 and Table 11. The highest cooling loading according to the analysis is 60.42 kWh. No solar heat gain was generated by space 2 because it has no fenestration.

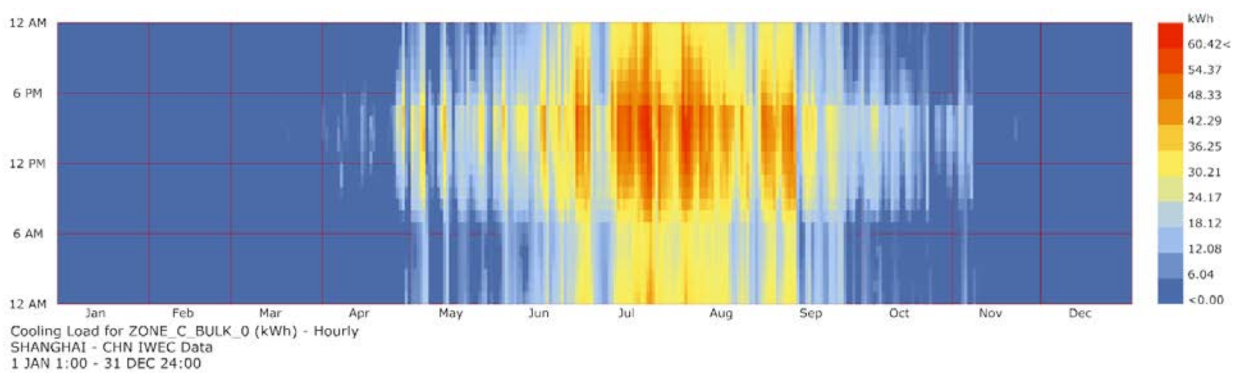


Figure 32 Zone C bulk space 2 cooling load (Monthly)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	1197	7302	15474	23477	22882	13500	3927	0	0

Table 11 Zone C bulk space 2 cooling load (Average)

3. Zone E Area

3.1 Warehouse - Zone E - warehouse office space cooling load

When comparing the cooling load for zone E office space (Figure 33 and Table 12) to the cooling load for zone A office space, the result is nearly the same. This is because the two areas have the same floor area and same size of windows. The highest cooling load according to the analysis is 26.23 kWh, which appears in 7 am. The cooling period is from April to October. Solar heat gain for zone E office space is presented in Figure 34 and Table 13. The highest solar heat gain is 7.22 kWh, which appears in 7 am also.

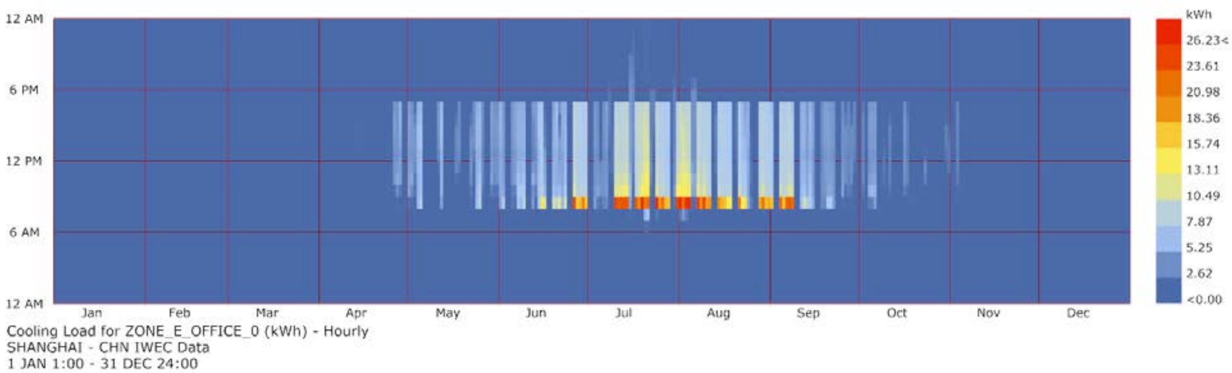


Figure 33 Zone E office space cooling load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	76.8	452.4	1058.7	1697	1801.6	903.5	165.7	0	0

Table 12 Zone E office space cooling load

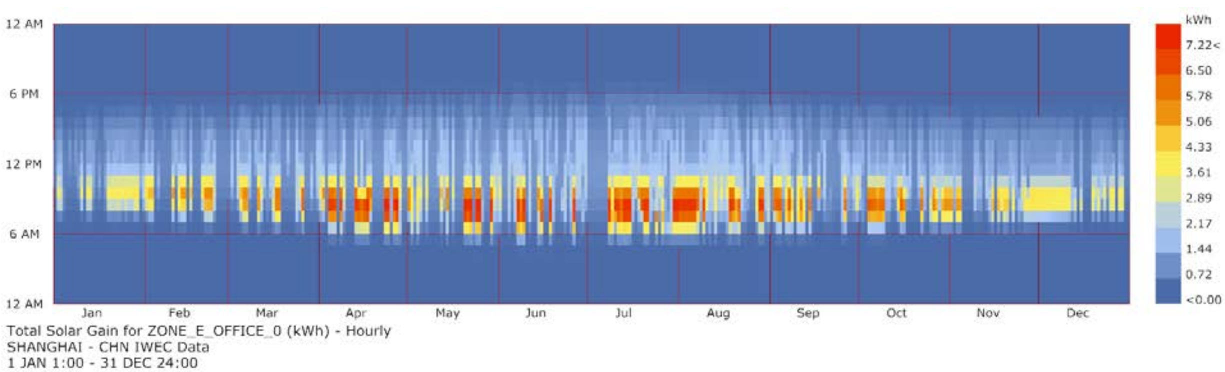


Figure 34 Zone E office space solar heat gain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
kWh	301	314	380	583	543	504	658	697	448	481	346	341

Table 13 Zone E office space solar heat gain

3.2 Warehouse - Zone E - warehouse bulk space cooling load

The cooling load for zone E bulk space is presented in Figure 35 and Table 14. The highest cooling loading according to the analysis is 51.09 kWh. Solar heat gain for zone E bulk space is presented in Figure 36 and Table 15. The highest solar heat gain is 4.28 kWh. Bulk space E faces to the north, which does not receive any direct sun light. All the daylighting is diffused type. As a result, the space is not receiving a significant solar heat. The movement of each month date is slight.

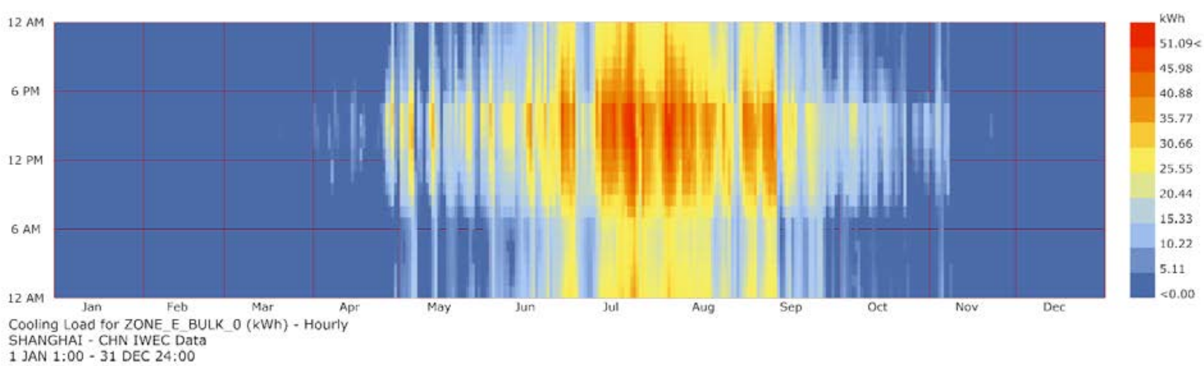


Figure 35 Zone E bulk space cooling load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	1066	6320	13150	19534	19318	11414	3430	0	0

Table 14 Zone E bulk space cooling load

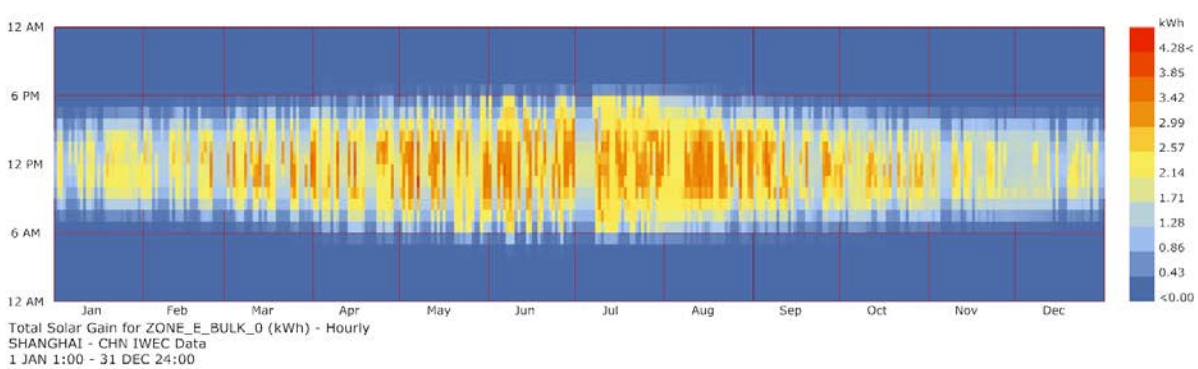


Figure 36 Zone E bulk space solar heat gain

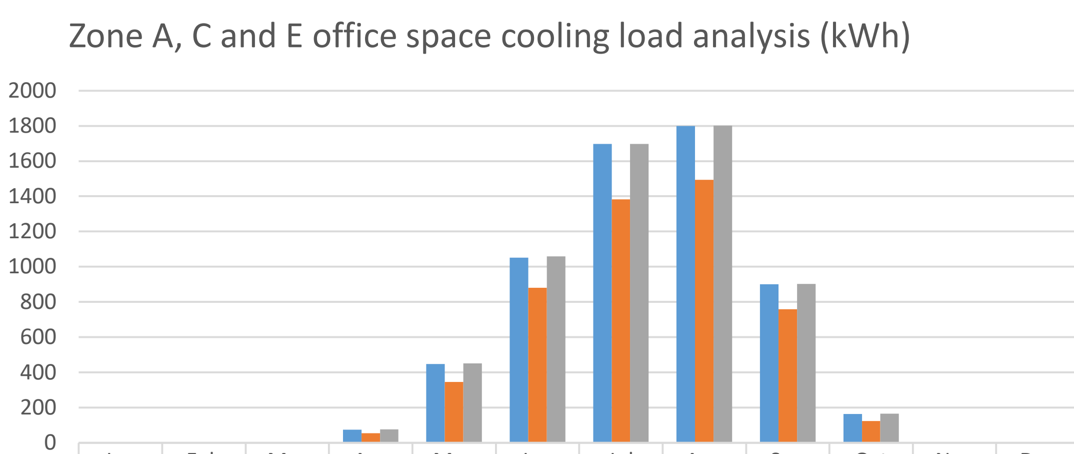
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
kWh	356	341	498	572	684	728	778	757	535	478	373	329

Table 15 Zone E bulk space solar heat gain

4. Conclusion of existing building annual energy condition

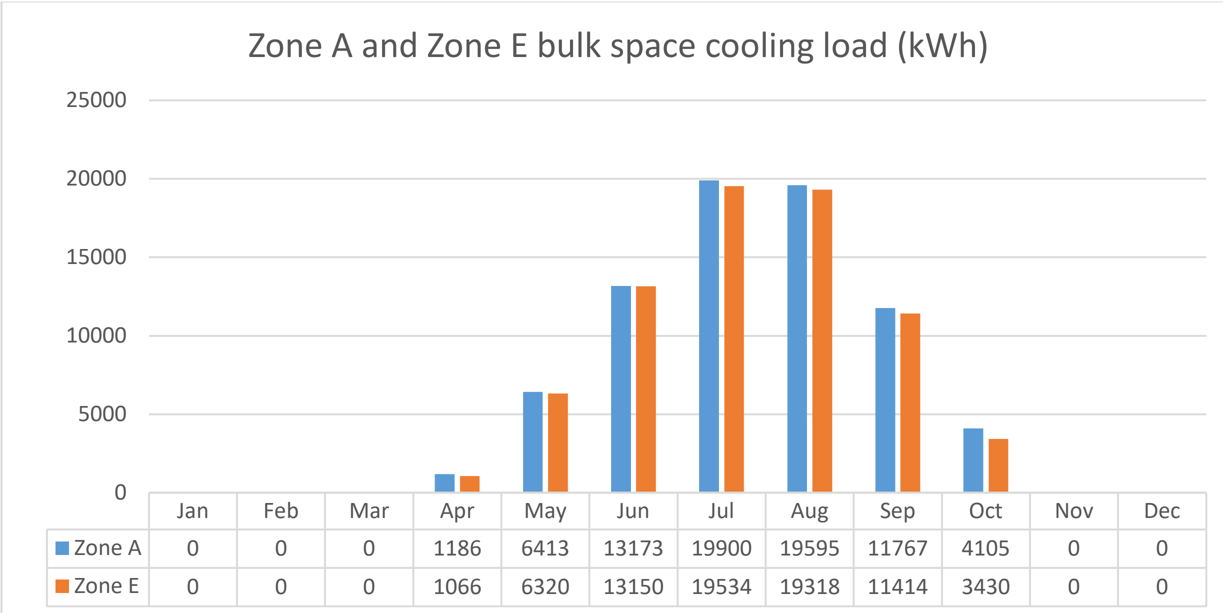
It should be noted that the analysis for zone C bulk space is generated separately for its difference. The cooling load for office space in zones A, C, and E are presented in Figure 37. The cooling load for the bulk space in zones A and E are presented in Figure 38. The cooling load for the bulk space in zone C (spaces 1 and 2) are presented in Figure 39. Solar heat gain for office space in zones A, C, and E are presented in Figure 40. Solar heat gain for the bulk space in zones A and E are presented in Figure 41. Overall, 11.2% of regular occupied area is receiving desirable daylighting.

The cooling load for the office is less than that of the bulk space because the office is smaller in size. The office in zone C has the lowest cooling load compared to other office spaces, because it has a smaller window size. The bulk space in zone E has a lower cooling load because it faces north.



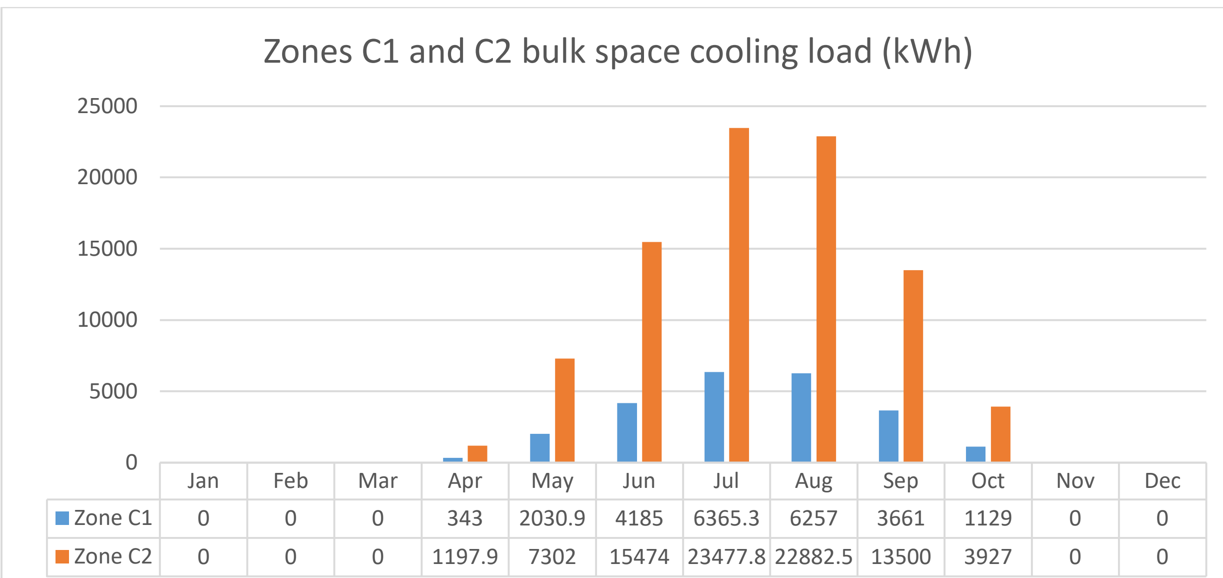
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone A office	0	0	0	75	448	1052	1698	1800	900	163	0	0
Zone C office	0	0	0	55.6	344.9	879.7	1383.5	1493.6	758.2	123.2	0	0
Zone E office	0	0	0	76	452	1058	1697	1801	903	165	0	0

Figure 37 Zones A, C, and E office bulk cooling load analysis from April to October



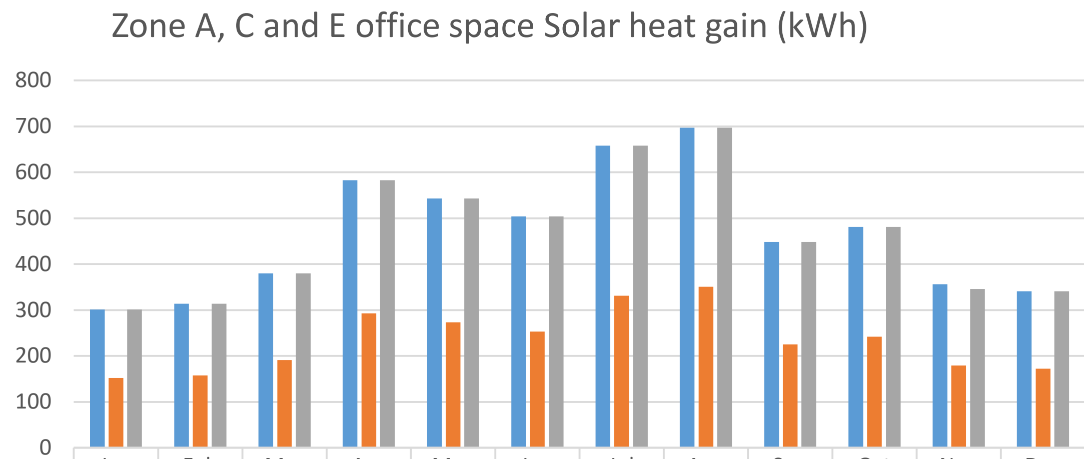
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone A	0	0	0	1186	6413	13173	19900	19595	11767	4105	0	0
Zone E	0	0	0	1066	6320	13150	19534	19318	11414	3430	0	0

Figure 38 Zones A and E bulk cooling load analysis from April to October



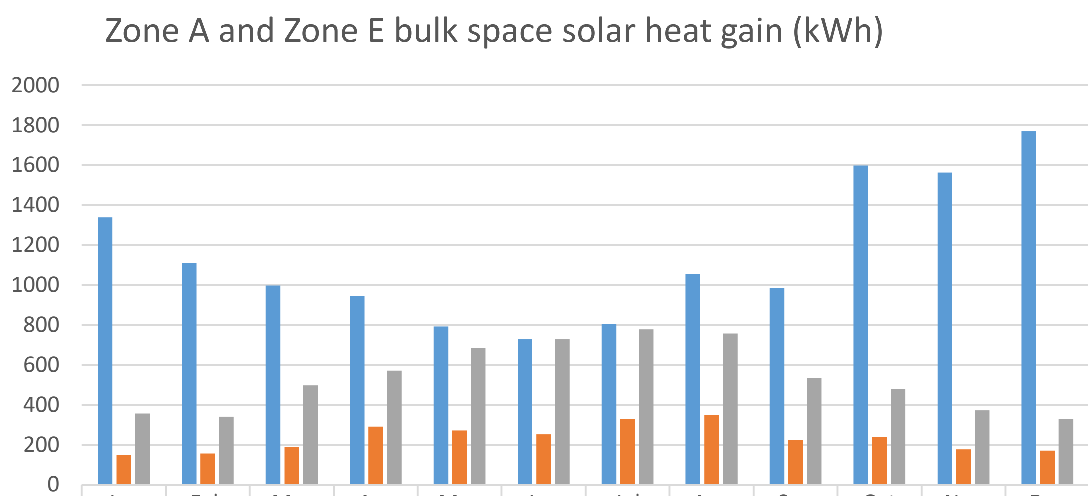
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone C1	0	0	0	343	2030.9	4185	6365.3	6257	3661	1129	0	0
Zone C2	0	0	0	1197.9	7302	15474	23477.8	22882.5	13500	3927	0	0

Figure 39 Zones C1 and C2 cooling load analysis from April to October



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone A office	301	314	380	583	543	504	658	697	448	481	356	341
Zone C office	152	158	191	293	273	253	331	351	225	242	179	172
Zone E office	301	314	380	583	543	504	658	697	448	481	346	341

Figure 40 Zones A, C, and E office space solar heat gain



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone A bulk	1339	1111	998	945	792	728	806	1055	985	1598	1563	1769
Zone C bulk 1	150	157	189	291	271	252	329	348	224	240	177	170
Zone E bulk	356	341	498	572	684	728	778	757	535	478	373	329

Figure 41 Zones A and E bulk space solar heat gain

V. Renovation Design Improvement

Based on the early daylighting analysis of this warehouse, it could be concluded that the majority of the warehouse-bulk space has little access to daylight. Therefore, the expectation of the renovation design is to achieve 1 point standard of daylight (Option 1, LEED O+M: Existing Buildings V4). Once 55% of the regularly occupied floor area is inaccessible to natural daylighting (which is between 100 and 2000 lux), the design goal of the improvement of daylight is considered to be achieved.

The second conclusion of the cooling analysis section is that both office space and bulk space have a high cooling load. The expectation of the renovation design is to reduce the cooling load by 20% and to apply natural ventilation successfully to attain the prerequisite credits of minimum indoor air quality performance of LEED O+M: Existing building V4.

The first renovation applies passive daylighting to reduce the illumination energy consumption, and offering a better working environment for the warehouse staff.

The second renovation applies passive cooling to reduce mechanical consumption, concurrently allowing staff greater access to fresh air.

1. Strategy I: Daylighting

Before beginning the new fenestration design, a sample test is required to understand the existing radiation analysis, which will help to determine the location and the size of the new fenestration. The south side wall and the east side wall usually have more potential to gain solar heat compare to the north side wall and the west side wall in the Northern Hemisphere. This statement analysis is tested in the following section. Large fenestration will bring increased daylighting, whilst more solar heat will be gathered. As a result, the cooling load might be increased. The window-to-wall ratio is calculated as the ratio of the wall fenestration area to the gross wall area. Window sill height is measured from the ground to the bottom edge of windows. Window area has a direct influence on a building's heating, cooling, and lighting systems, which can also impact the passive strategy such as natural daylight, and natural ventilation.

1. Sample testing

A simple test was required to support the new window design and to establish the correct window-to-wall ratio for each side of the building. Each side of wall was tested separately. There are two variables that can influence the daylighting analysis: the window's sill height and the window size. These two variables directly affect daylighting illumination and cooling load of the test-building modeling. To determine the best window-to-wall ratio, these two factors need to be measured to establish an acceptable window sill height and window size compromise that can provide a good daylighting result whilst not generating a high cooling load.

The set range of window sill height is between 1.5 and 2.5 m, and the set range for window-to-wall ratio is 0.1 to 0.9 (0% to 90%). This sample testing is a 30 x 30 x 10 m building using weather date for the same location. The date and time selected for this sample testing was March 21st at 9 am with the clearest sky condition. A total of 90 (10 x 9) terms were entered to run the testing analysis.

Design Explorer software was applied to visualize the data, providing results to support the development of a best solution for both acceptable cooling load and daylighting illumination for the entire floor space.

First, all data analysis is conducted by Grasshopper™ corporate with Ladybug tools. An excel sheet was generated automatically at the same time. Then uploading the excel sheet into Design Explorer, a nice clean graphic is created. Here is an example to help the readers to understand how to use the software and what is the analysis results mean.

There are four columns in Figure 42, the first column is wall ratio, the second column is sill height, the third column is cooling load, the last one is daylighting. All these value can be selected and manipulated. Each term is mapped to its own cooling load and daylighting illumination result. In Figure 42, 0.5 wall ratio is corresponding to 10 possible sill height, which is from 1.5 m to 2.5 m. Different value of sill height does not influence the cooling load in this case. Once the wall ratio is set, the amount of sun heat can be received by the floor area does not change. However, the amount of daylighting has a slightly difference.

The green line is read as when a 0.5 wall ratio with a 2.5 m sill height will generate 31,000 watts of cooling load, and the floor area will receive 240,000 lux of daylighting. The red line is read as when a 0.5 wall ratio with 1.5 sill height will generate 31,000 watts of cooling load, and the floor area will receive 250,000 lux of daylighting.

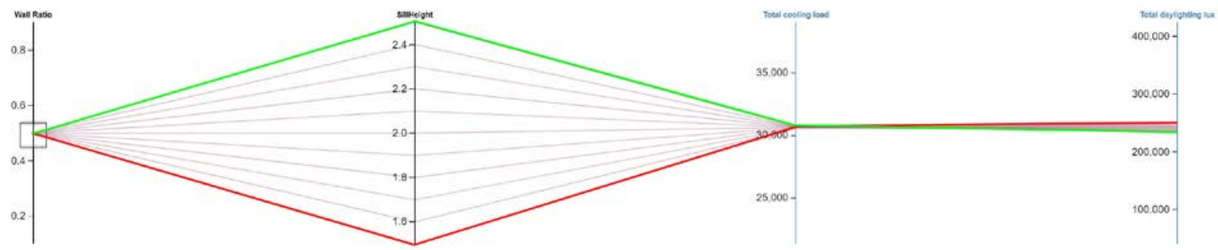


Figure 42 Sample explanation

Please notice that, these four factors were only collected for this test research. There are other factors that can affect daylighting and cooling as well as the window size and sill height. Therefore, the cooling load analysis is much more complex than what was tested in this paper.

However, the method of making decision to find out the proper wall ratio and sill height, is opposite. The selection is from right to left. A basic range of daylighting and cooling load has to be selected first based on common sense as a starting point, to understand the entire logic of this testing analysis. Dependent upon the variables and the data input, the testing result might provide an appropriate result, or not. Therefore, it should be adjusted accordingly.

1. East wall testing

Figure 43 presents all possible situations for the east wall, with different wall ratios and sill heights. The selection of daylighting range are presented in Figure 44. The acceptable range of total floor illumination is between 150,000 and 300,000 lux. The selection for cooling range are presented in Figure 45. The acceptable range of cooling load is between 15,000 and 28,000 W. When the window-to-wall ratio of the east wall is between 0.3 to 0.4, the full range of sill heights has the same influence on cooling load and total illumination. The cooling load can be regulated between 26,000 to 28,000 W, while the total floor illumination is still able to reach 150,000 to 200,000 lux. The final selection is presented in Figure 46.

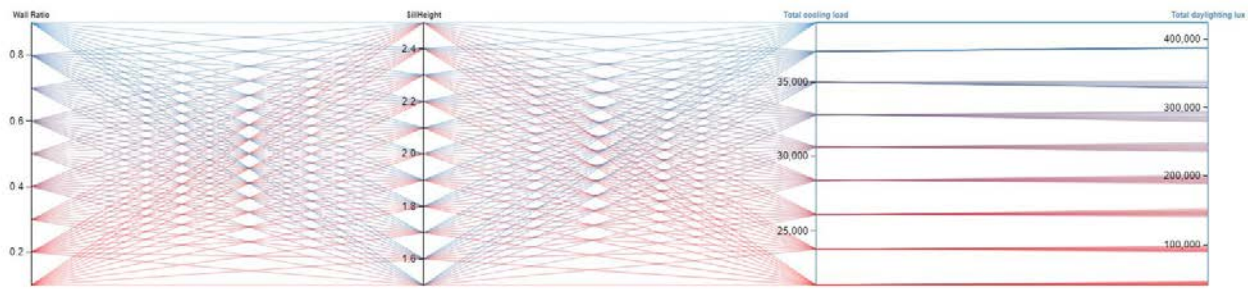


Figure 43 East wall analysis result (all) https://goo.gl/VxdwZk

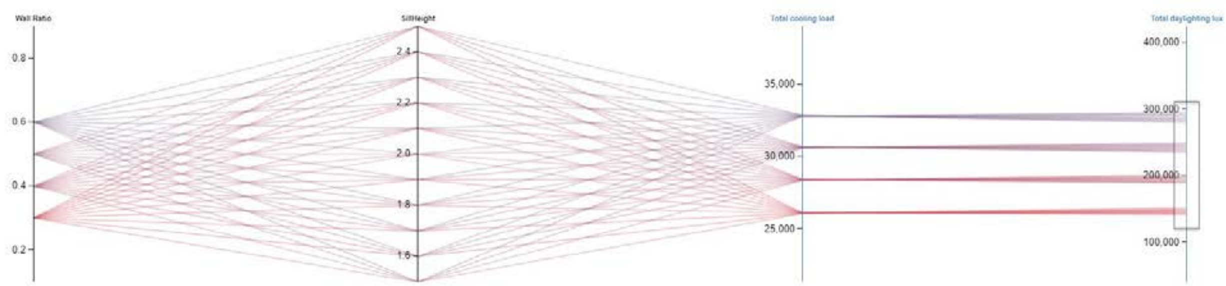


Figure 44 East wall analysis result (lux) https://goo.gl/VxdwZk

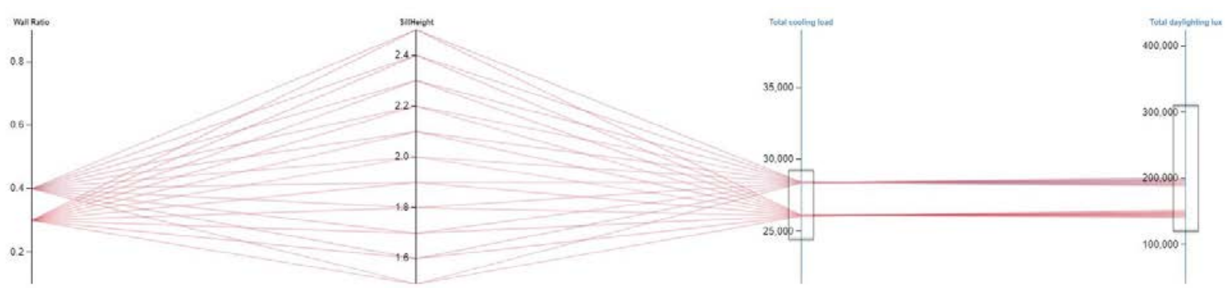


Figure 45 wall analysis result (watts) https://goo.gl/VxdwZk

Figure 46 Final selection) https://goo.gl/VxdwZk

Testing building floor area will receive 150,000 lux of daylighting and generate 26,000 W of cooling load when the east window to wall ratio is 0.3 with a 1.7 m sill height.

2. South wall testing

Figure 47 presents all possible situations for the south wall with different wall ratios and sill heights. The selection for daylighting range are presented in Figure 48. The acceptable range of total floor illumination is between 150,000 to 330,000 lux. The selection for cooling range are presented in Figure 49. The acceptable range for cooling load is between 24,000 and 28,000 W. When the window-to-wall ratio of the south wall is between 0.3 to 0.5, the full range of sill heights has the same influence on the cooling load and total illumination. The cooling load can be regulated between 24,000 to 28,000 W, while the total floor illumination is still able to reach 150,000 to 250,000 lux. The final selection is presented in Figure 50.

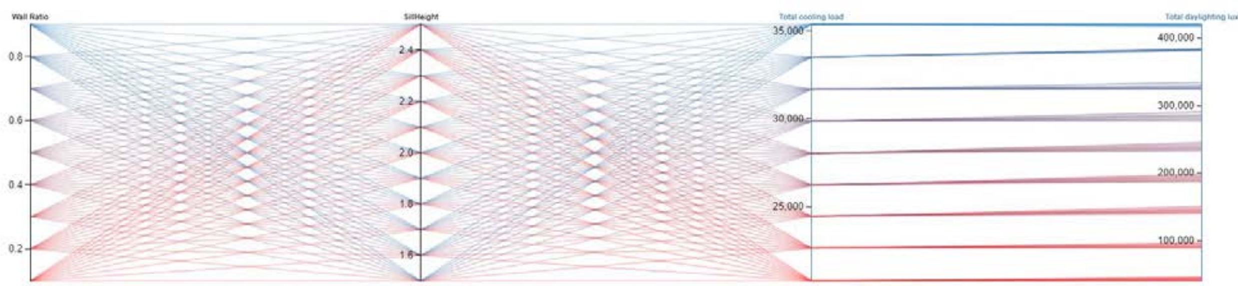


Figure 47 South wall analysis result (all) https://goo.gl/whRuUJ

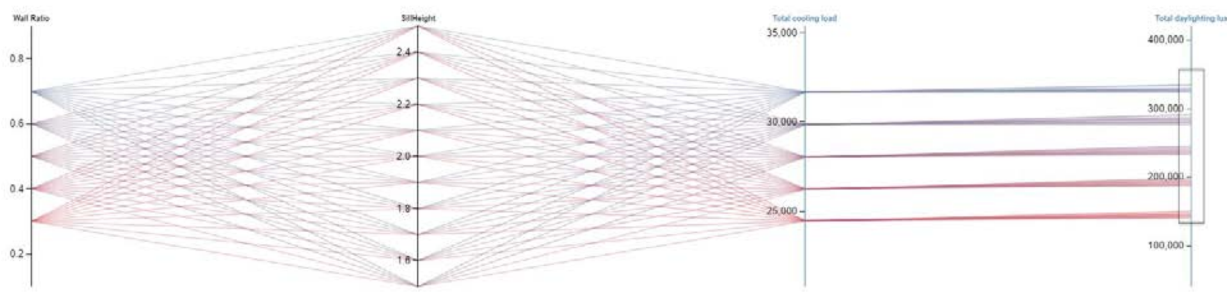


Figure 48 South wall analysis result (lux) https://goo.gl/whRuUJ

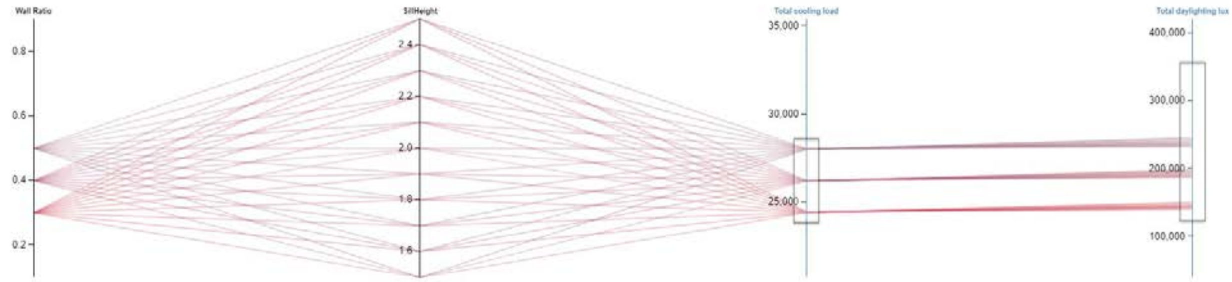


Figure 49 South wall analysis result (watts) https://goo.gl/whRuUJ

Figure 50 Final selection https://goo.gl/whRuUJ

Testing building floor area will receive 250,000 lux of daylighting and generate 28,000 W of cooling load when the south window to wall ratio is 0.5 with a 1.7 m sill height.

3. West wall testing

Figure 51 presents all possible situations for the west wall with different wall ratios and sill heights. The selection for daylighting range are presented in Figure 52. The acceptable range of total floor illumination is between 150,000 and 280,000 lux. The selection for cooling load range are presented in Figure 53. The acceptable range for cooling load is between 26,000 and 32,000 W. When the window-to-wall ratio of the west wall is between 0.3 to 0.5, the full range of sill heights has the same influence on the cooling load and total illumination. The cooling load can be regulated between 26,000 and 35,000 W, while the total floor illumination is still able to reach between 190,000 and 240,000 lux. The final selection is presented in Figure 54.

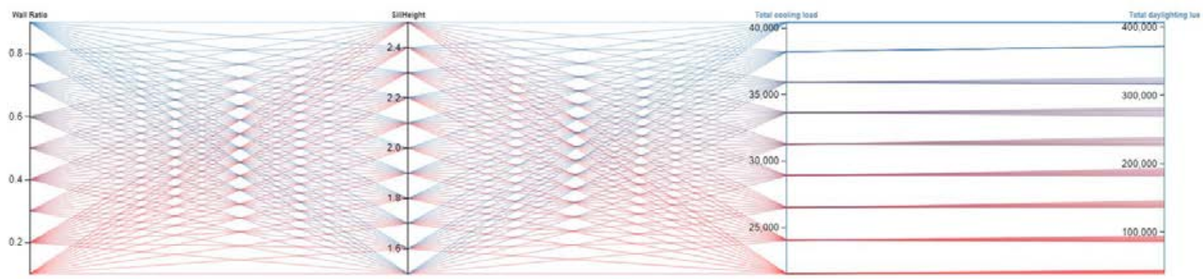


Figure 51 West wall analysis result (all) https://goo.gl/VznkfC

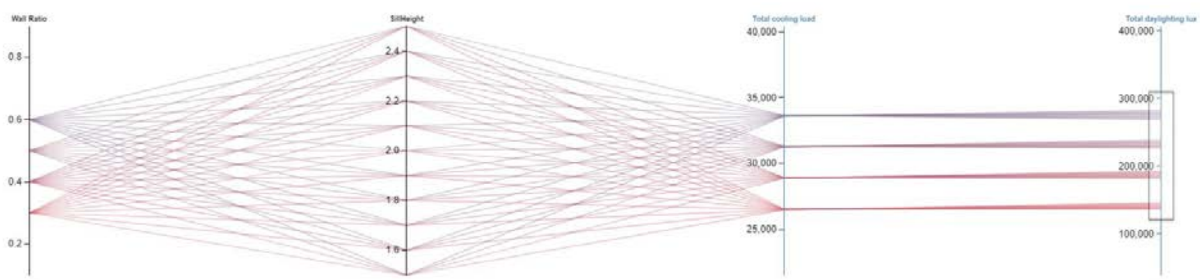


Figure 52 West wall analysis result (lux) https://goo.gl/VznkfC

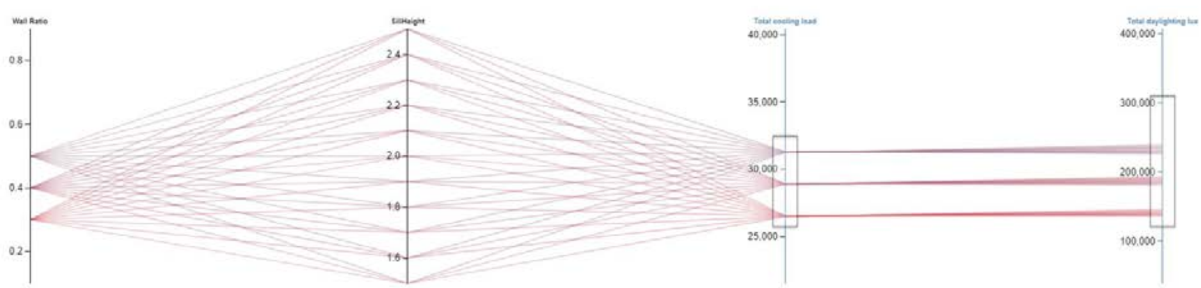


Figure 53 West wall analysis result (watts) https://goo.gl/VznkfC

Figure 54 Final selection https://goo.gl/VznkfC

Testing building floor area will receive 150,000 lux of daylighting and generate 26,000 W of cooling load when the west window to wall ratio is 0.3 with a 1.7 m sill height.

4. North wall testing

Figure 55 presents all possible situations for the west wall with different wall ratios and sill heights. The selection for daylighting range are presented in Figure 56. The acceptable range for total floor illumination is between 190,000 and 290,000 lux. The selection for cooling load are presented in Figure 57. The acceptable range for cooling load is between 24,500 and 29,000 W. When the window-to-wall ratio of the north wall is between 0.4 and 0.5, the full range of the sill heights has the same influence on the cooling load and total illumination. The cooling load can be regulated between 24,500 and 25,900 W, while the total floor illumination is still able to reach between 190,000 and 240,000 lux. The final selection is presented in Figure 58.

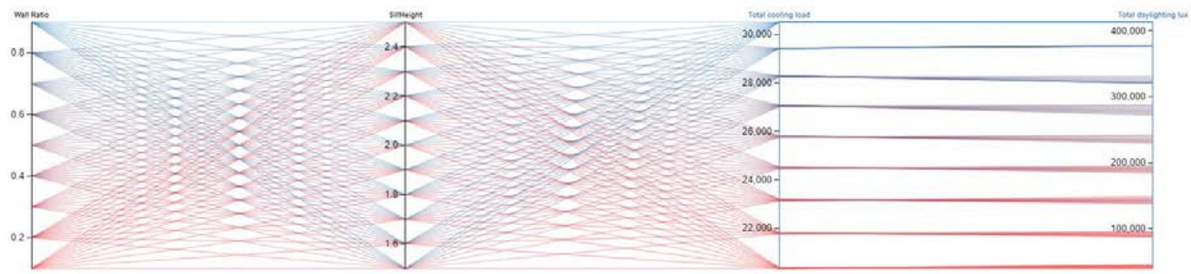


Figure 55 North wall analysis result (all)

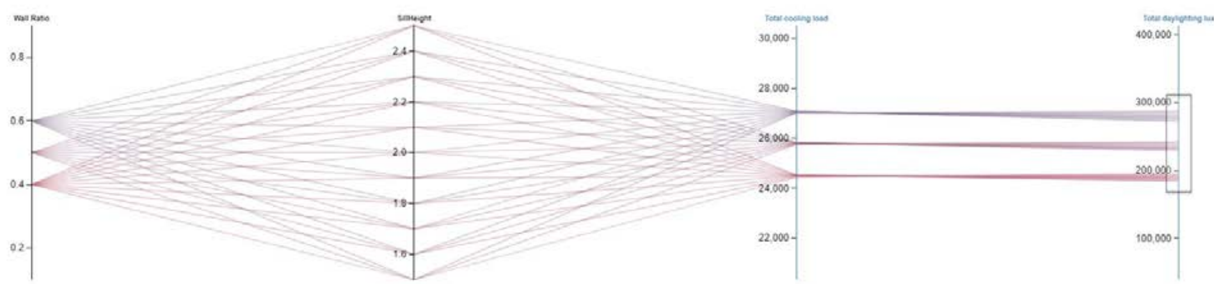


Figure 56 North wall analysis result (lux)

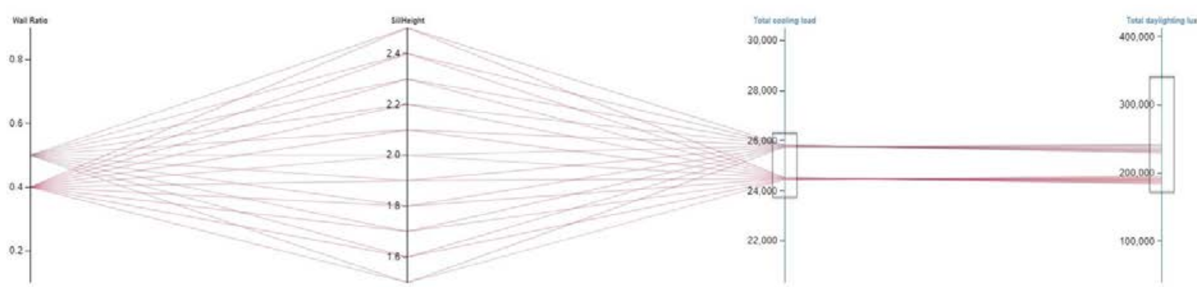


Figure 57 North wall analysis result (watts) https://goo.gl/j3KkT6

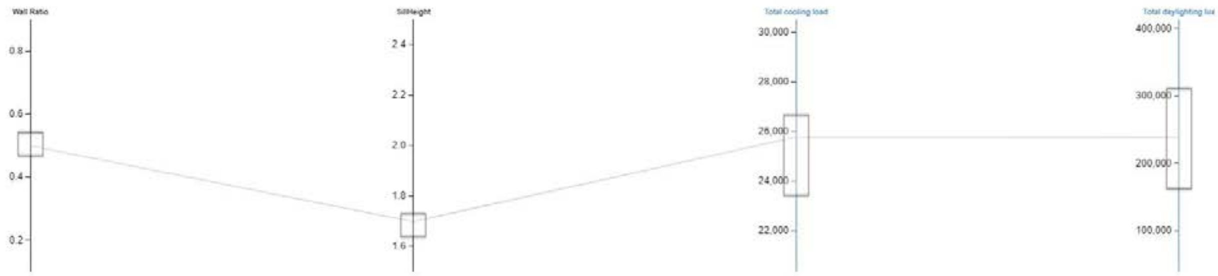


Figure 58 Final selection https://goo.gl/j3KkT6

Testing building floor area will receive 240,000 lux of daylighting and generate 25,900 W of cooling load when the north window to wall ratio is 0.5 with a 1.7 m sill height.

5. Testing results and conclusion

The final results indicate that the window to wall ratio of both the east and west walls have more impact on the building's cooling load and total floor illumination than the north and west walls for the building in this particular study location. Considering that this thesis is a renovation design, a minimum demolition change that can still achieve the design goal would be considered as a better solution. Therefore, the sill heights will remain at 1.7 m as the regional design, with reduced demolition. Figure 59 presents the window-to-wall ratio 3D modeling. The window-to-wall ratios for the east, south, west, and north walls are 0.3, 0.5, 0.3, and 0.5, respectively.

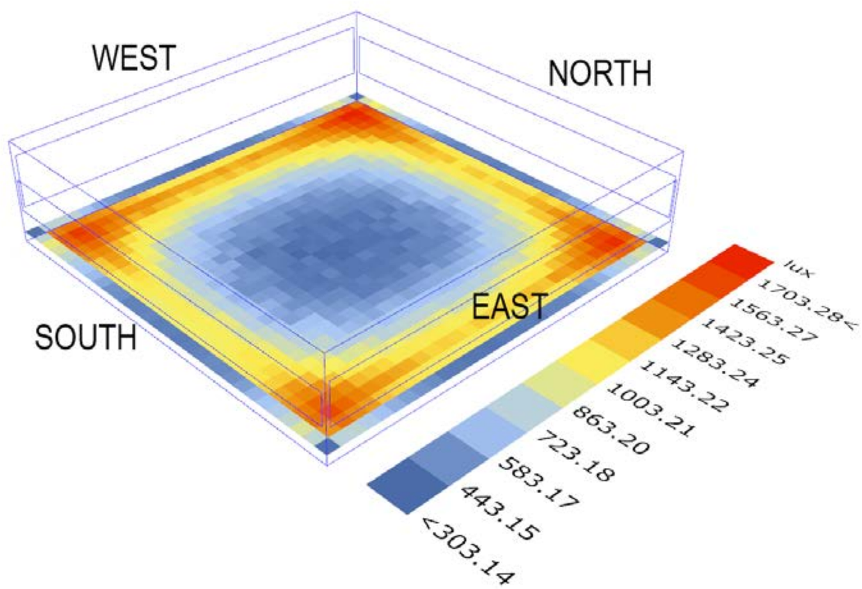


Figure 59 Testing 3D model

Therefore, applying the sample test results to this selected warehouse, the total opening areas on the east, north, west, and south walls should be 225, 180, 225, and 180 m^2, respectively. Consequently, ten new windows are required for the east wall. The new window's sill height can remain at 1.7 m, however, the window's height will be increased to 4.5 m and the window's width will be increased to 5 m. Two new windows are required for the north wall, with a sill height remaining at 1.7 m, the height increased to 5 m and the width revised to 16 m. Fifteen new windows are required for the west wall (1.7 m sill height, 3 m height, and 5 m width), and two new windows are required for the south wall (sill height 1.7 m with an increased height of 5 m, and increased width of 16 m).

Location	Quantity	Sill height	Window height	Window width
East	10	1.7 m	4.5 m	5 m
North	2	1.7 m	5 m	16 m
West	15	1.7 m	3 m	5 m
South	2	1.7 m	5 m	16 m

Table 16 New opening details

Results presented in Figure 60 indicate that after the alteration of new fenestration, 42.6% of the warehouse space is receives proper daylighting illumination, which is between 100 and 2000 lux. The improvement is significant, but still not sufficient to achieve 1 point of Leadership in Energy and Environmental Design, Building Operations and Management (LEED O+M): *Existing Buildings V4 Standard of Daylight Option 1*, which requires 55% of the regularly occupied floor area. Therefore, adjustment is needed.

By overlapping these two test result images, the blue area (right side) illustrates that either of the areas receive daylighting higher than 2000 lux or lower than 100 lux. For those areas (labeled as ①) receiving daylighting higher than 2000 lux, adding sun shading might help to improve the result. The size and quantity of the shading devices has been tested in the following paragraph. For those areas labeled ②③ receiving daylighting lower than 100 lux, increasing the opening size might help to improve the result. Changing the sill height might also be required to provide a satisfying result.

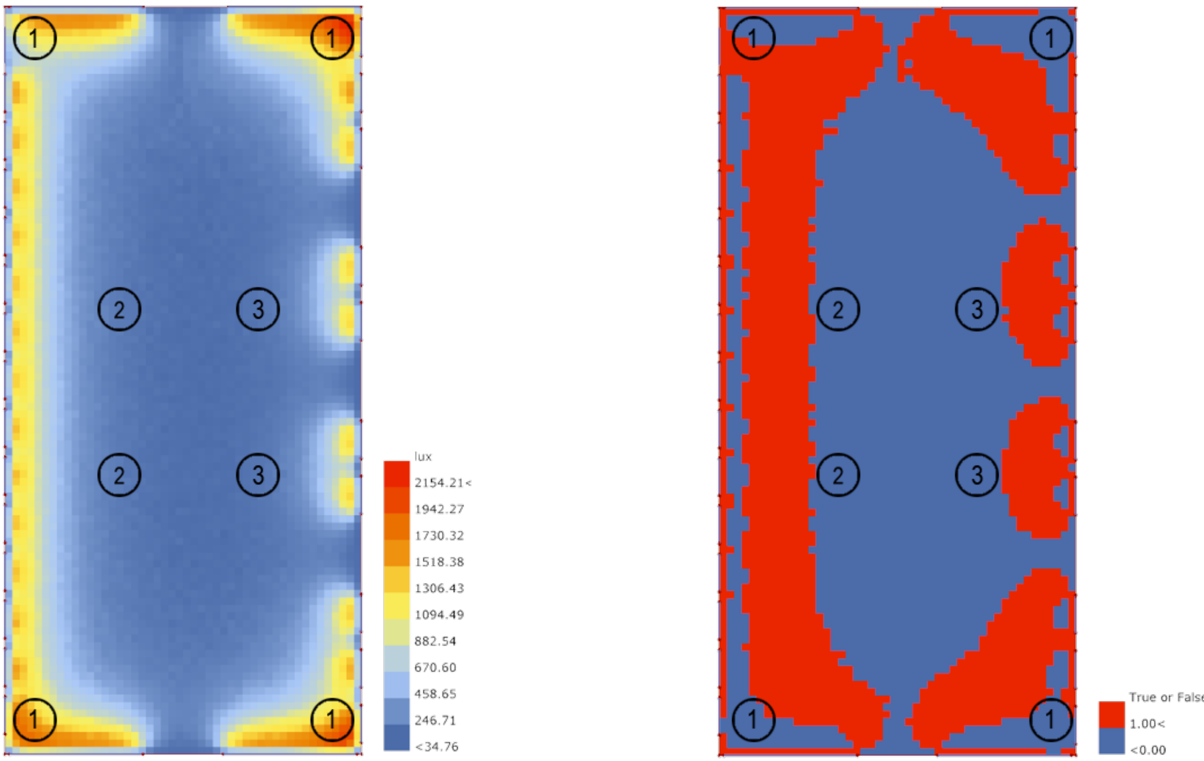


Figure 60 Option 1 result

2. Adjustment of Strategy I

1. Adjustment step 1: west wall improvement

Results presented in Figure 61 indicate that the total qualified area percentage increased to 43.2% when the window-to-wall ratio increased to 0.4. The new window's height increased to 4 m, and the width remained at 5 m. Raising the window's sill height to 2.0 m increased the qualified area percentage to 44.1%. This increase is not significant. Although more of the internal area is receiving daylighting, there is more area that is overexposed at the same time. Results presented in Figure 62 suggest that adding a shade device to each window will help to reduce the amount of overexposure. The shade device depth is 1 m and the distance between each panel is 3 m. Two shade devices were added to each window on the west wall. The shade device was installed at the top edge of each window. Results presented in Figure 63 show that the qualified area percentage increases to 45.6%. However, some daylighting is blocked by the shade device. Using a shade device to reflect daylighting into the interior space is a common solution to help extend the range of natural illumination. By dropping the shade device by 1 m this will help to achieve this result. Results presented in Figure 64 suggest that a total of 46.3% of the internal area is receiving acceptable daylighting.

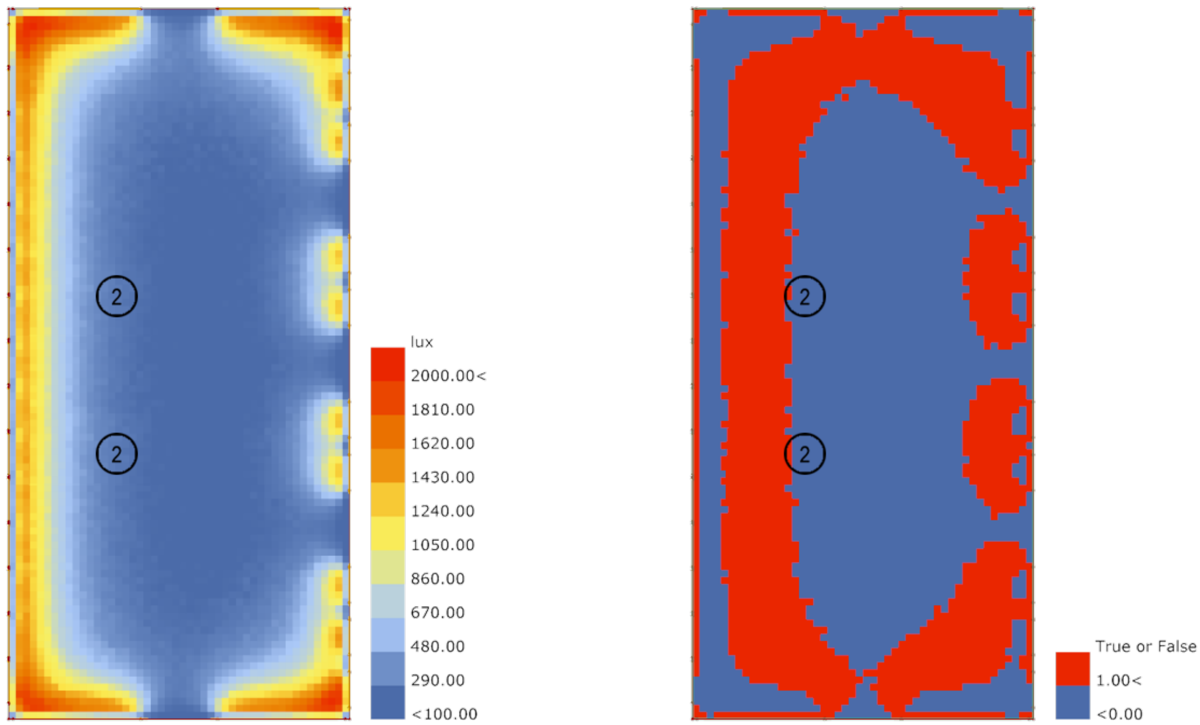


Figure 61 window to wall ratio 0.5

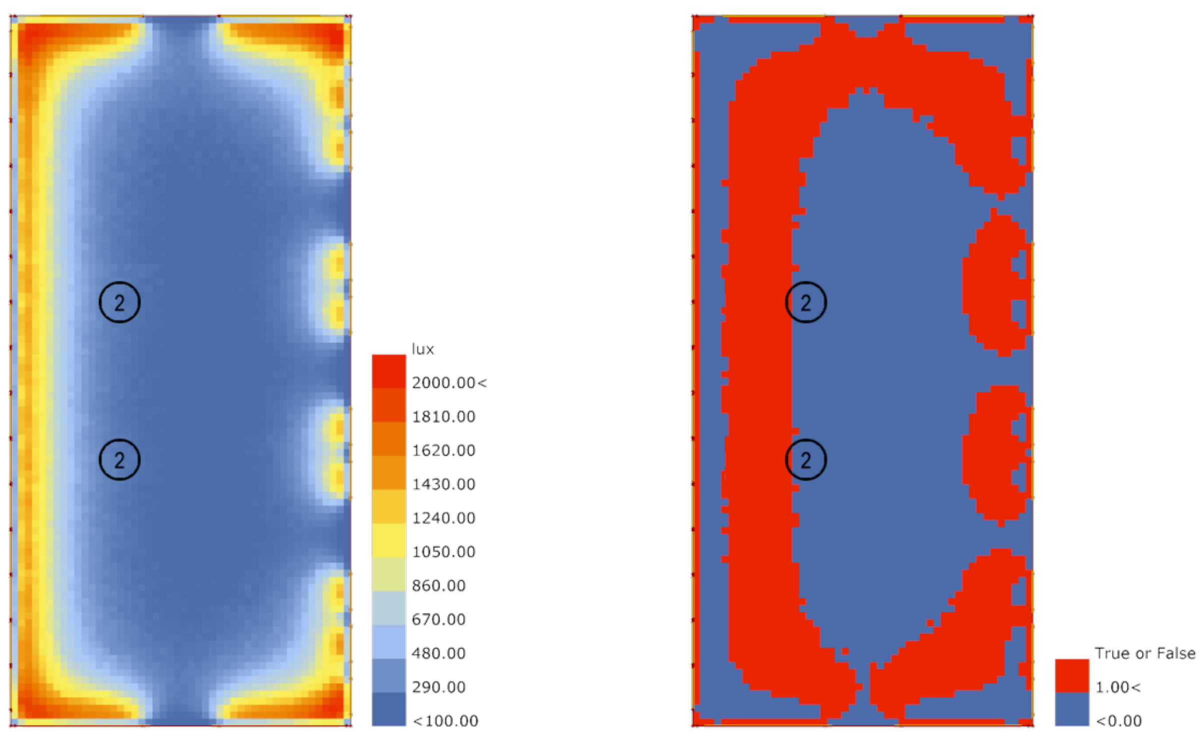


Figure 62 2m sill height

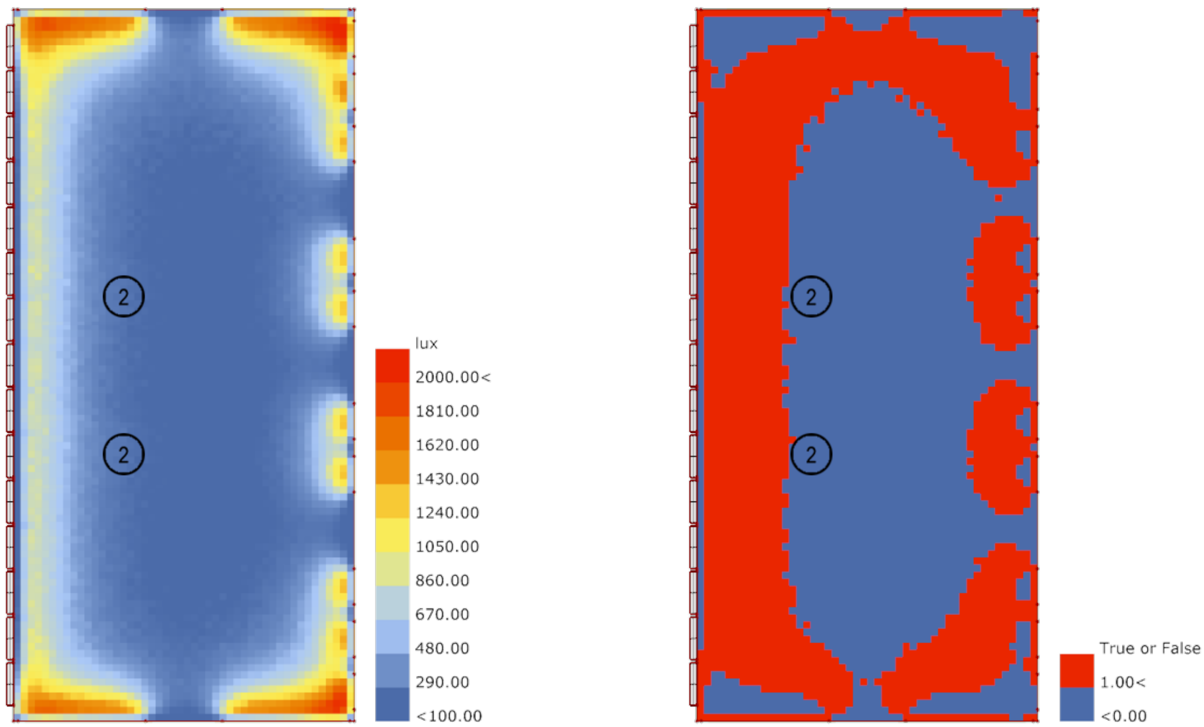


Figure 63 2 shade

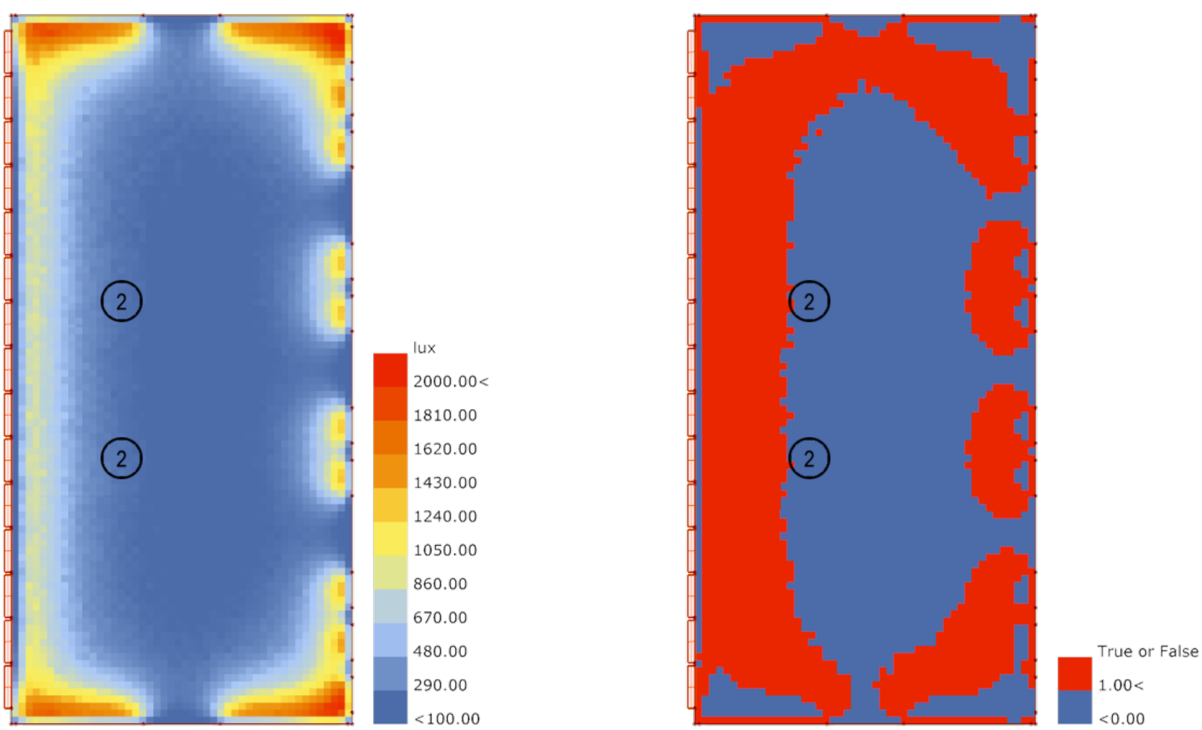


Figure 64 drop 1

2. Adjustment step 2: north wall improvement

As Figure 60 illustrates, the issues for the north side area (labeled as ①) is over glazing. Reducing the size of the windows and adding a shade device are ideal solutions. The first step is to reduce the window-to-wall ratio to 0.4. The new window size is changed to 5 m height and 7.2 m length, whilst the sill height remains at 1.7 m. Results in Figure 65 show that 46.8% of the total area is receiving desirable daylighting. Comparing Figure 60 to Figure 64 is is evident that the percentage of overexposure area is reduced, although the improvement is minimal. By reducing the window-to-wall ratio, less demolishment of the warehouse is required, which is a positive feature of a renovation project. However, this is not satisfactory. Further shade is needed to make greater improvements. Two shades of 1 m depth each are added on the north window. The shade device is located 1 m from the top edge of the window, with a distance of 3 m between shades. Result in Figure 66 suggest that 47.0% of the floor area is in acceptable qualified daylighting.

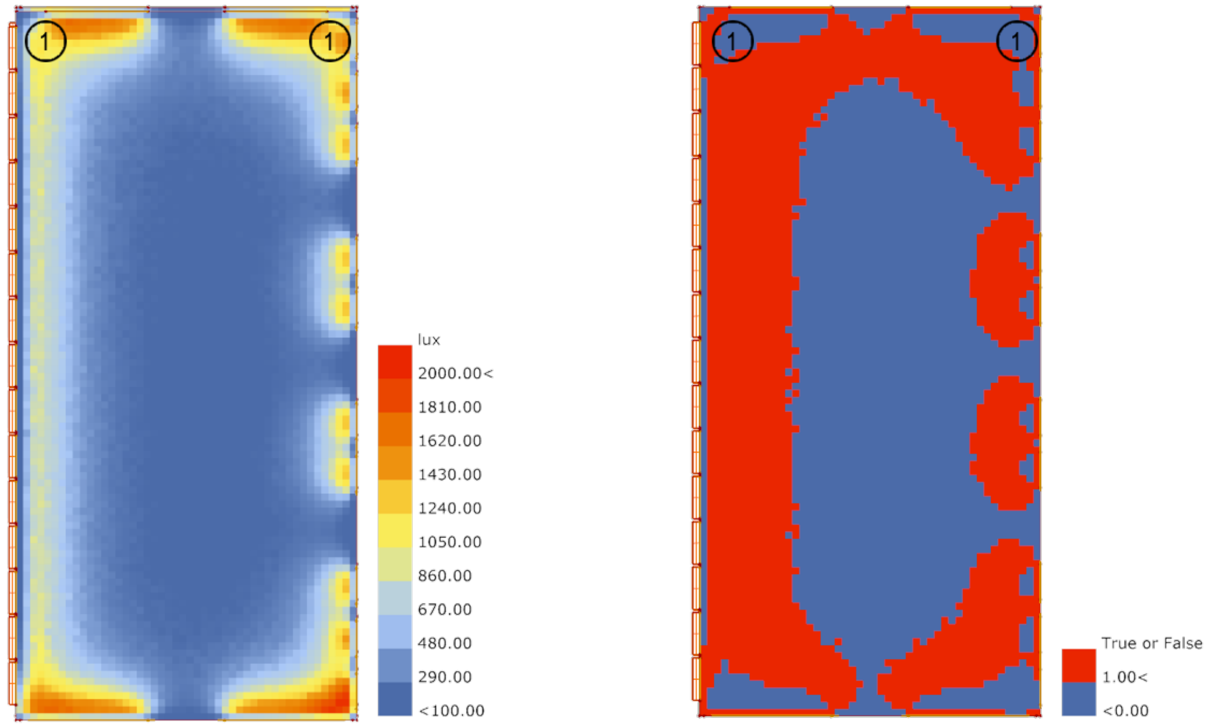


Figure 65 0.4 ratio

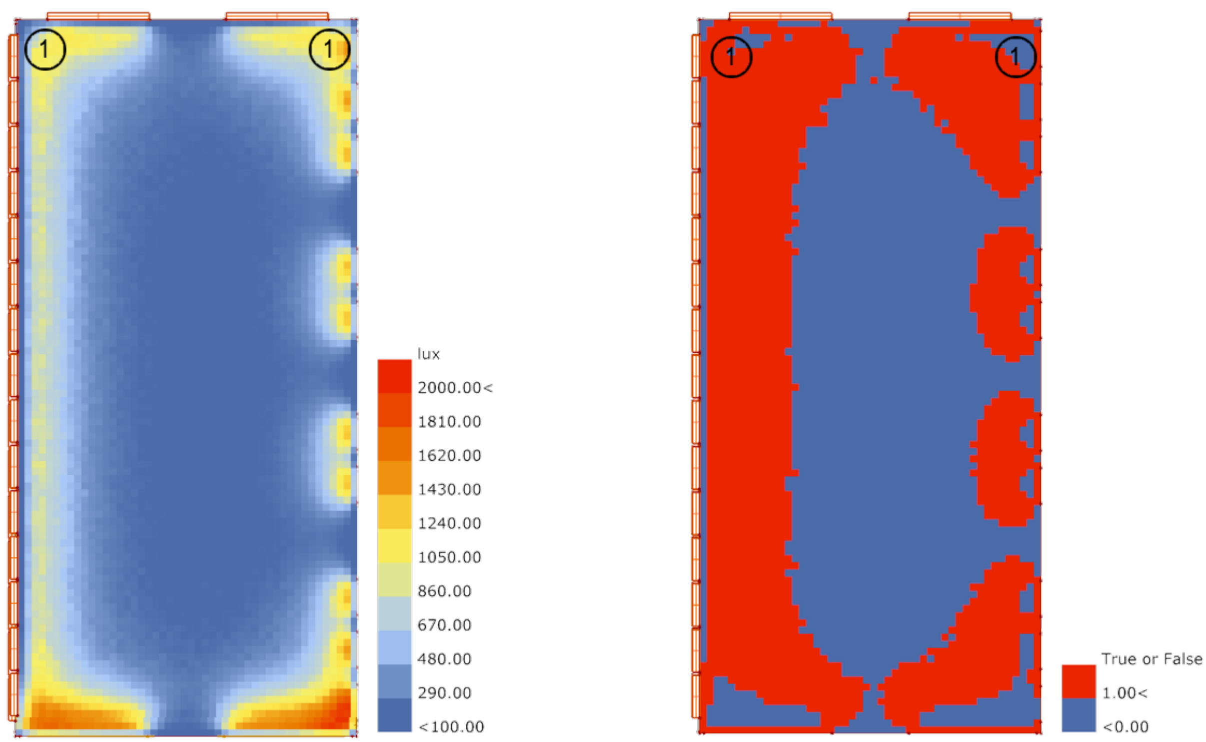


Figure 66 2 shades

3. Adjustment step 3: east wall improvement

Based on the results, the east side of the warehouse requires more daylighting to illuminate the interior space. Increasing the fenestration area would be the ideal solution. 0.4 window to ratio is set up to the east wall for improvement. The window size is 5 m height by 6 m width. The result presented in Figure 67 illustrates that 50.4% of the entire floor area is achieving acceptable daylighting. However, for the area that is labeled as ③, there is still not enough daylighting. By raising the window sill height to 2.0 m the qualified area percentage increases to 51.8%, as indicted in Figure 68. Sun rises in the east and sets in the west. The direct daylighting that east side of the warehouse can achieve is a low angle light beam. A lower shade device can help to reflect more daylighting to the deeper floor area. Based on the test results, only one area of shade is required for the east side of the warehouse, which is 1 m higher than the lower edge of each window. Adding one shade device enables 52.4% of the floor area to receive acceptable daylighting, as the result in Figure 69 illustrates.

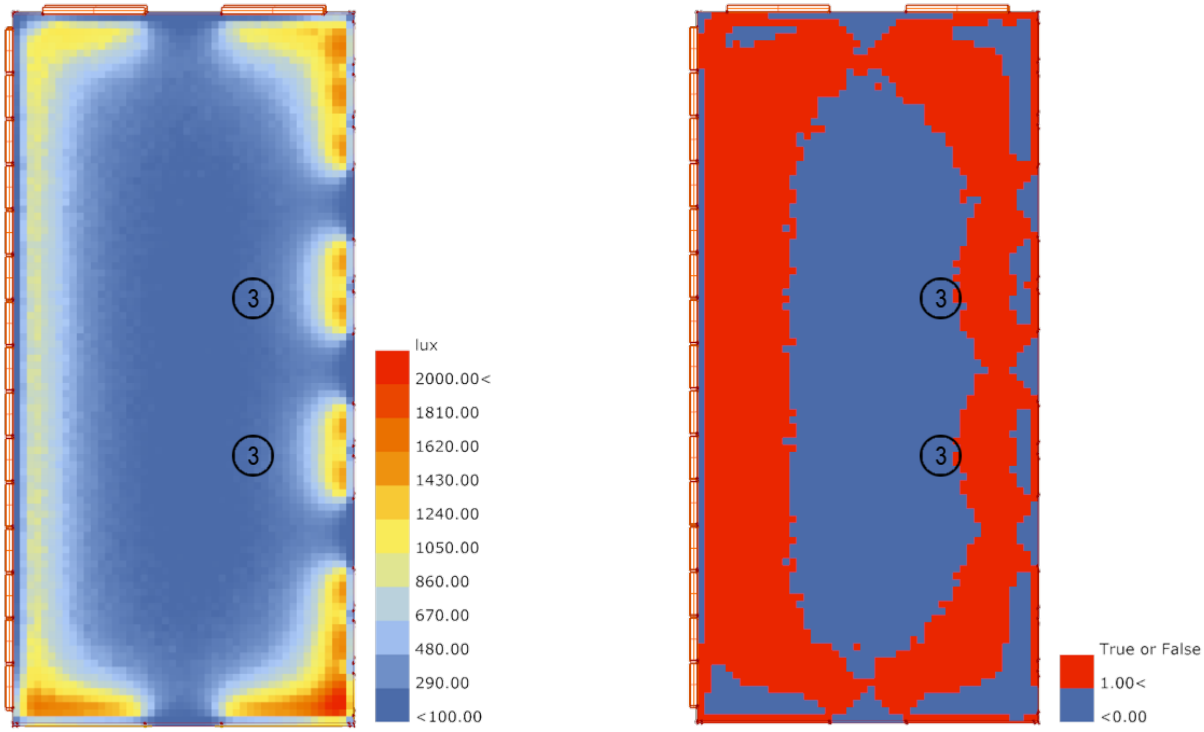


Figure 67 0.4 ratio

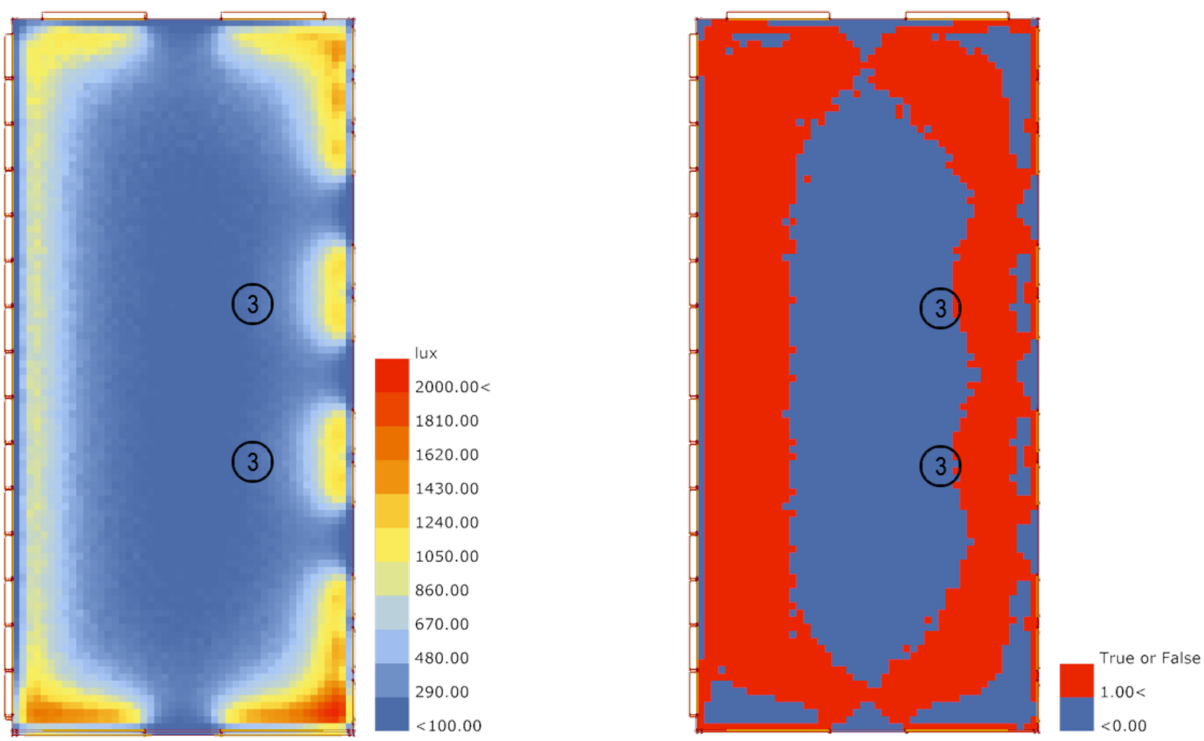
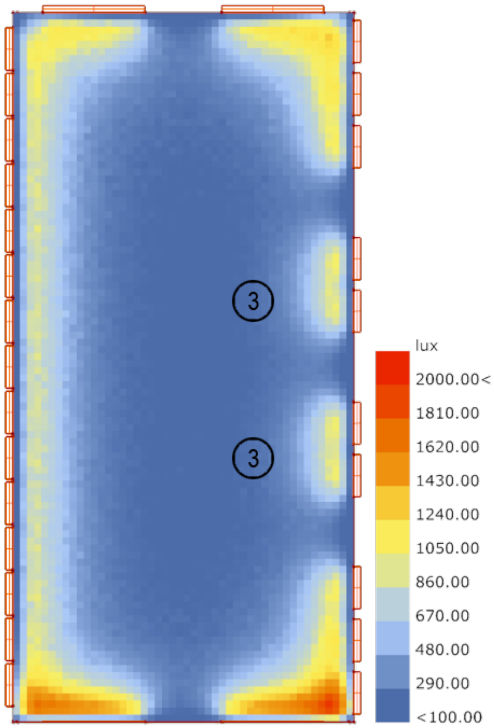


Figure 68 +0.3m



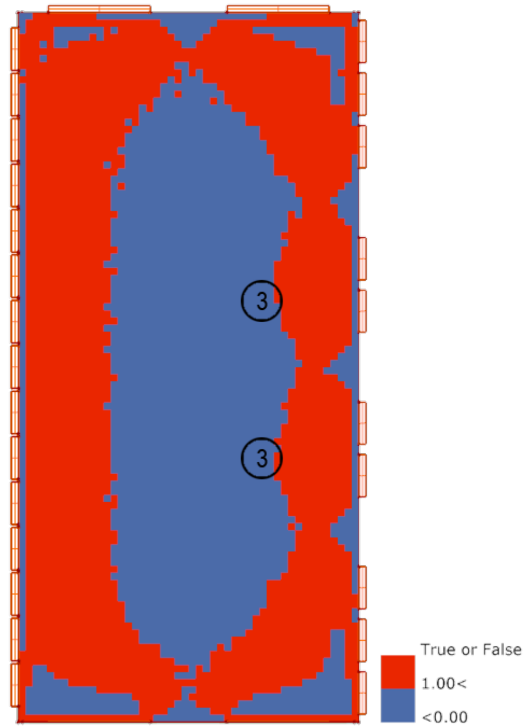


Figure 69 1 shade

4. Adjustment step 4: South wall improvement

The major problem for the south side of the warehouse (labeled as ①) is receiving unwanted daylighting. Reducing the size of openings and adding shade devices are ideal solutions. The first step is to reduce the window-to-wall ratio to 0.4. The results in Figure 70 indicate that 54.6% of the total floor area receives acceptable daylighting. Although the window-to-wall ratio is reduced, the area labeled as ① is still overexposed. Therefore, a shade device is required to help block unwanted daylighting. The south side of the warehouse receives a high-angle light beam, which indicates that more shade device is needed to block the direct daylighting. Three shade devices are added to each window on the south wall. The shade device is installed at the top edge of each window. The devices needed for each window have a 1 m depth and 2 m distance between each shade device. The result in Figure 71 indicates that 55.4% daylighting is achieved.

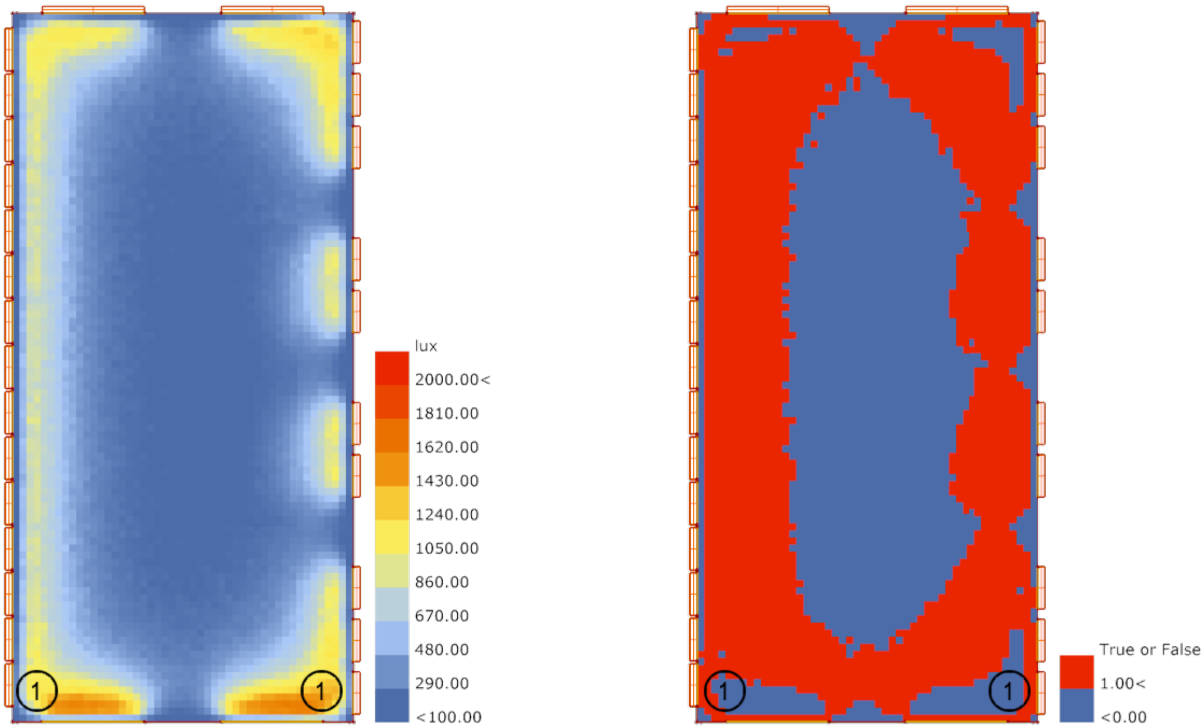


Figure 70 0.4 ratio

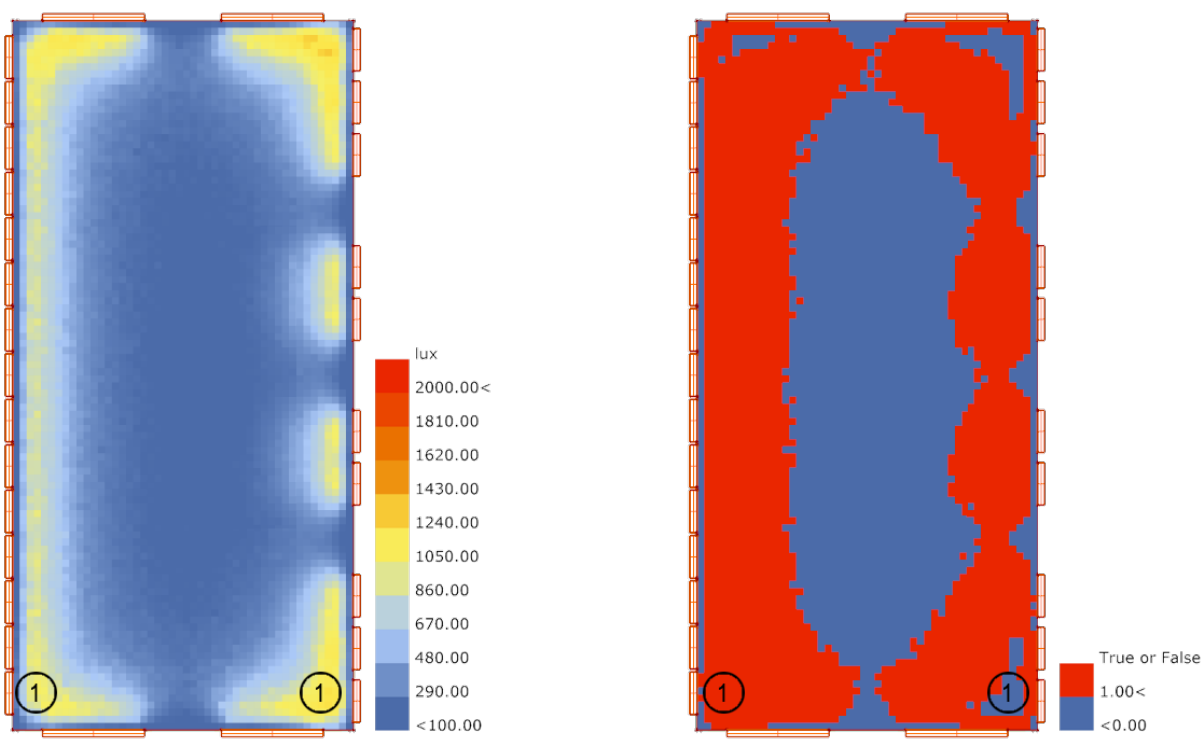


Figure 71 3 shade

5. Renovation summary of Strategy I

The first renovated 3D modeling is presented in Figure 72. The window-to-wall ratios for the east, south, west, and north walls are all 0.4.

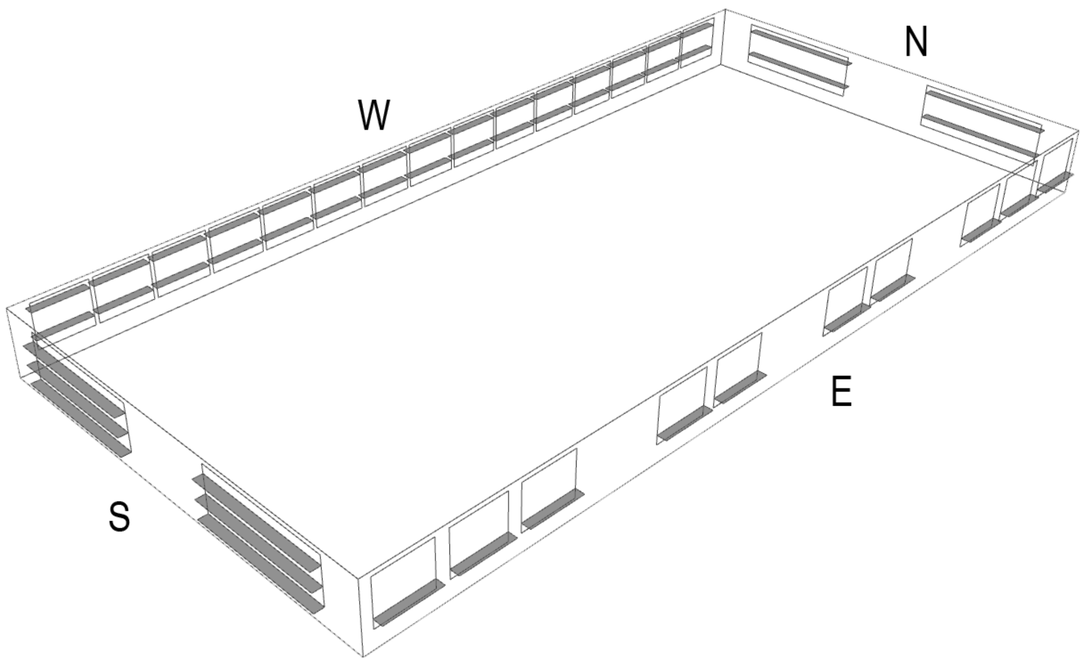


Figure 72 First renovated 3D modeling

The new renovated window opening details are provided in Table 17.

Opening Location	Opening Quantity	Sill Height	Window Height	Window Width	Shade per opening	Shade Depth	Distance between shades	Distance from top edge
East	10	2 m	5 m	6 m	1	1 m	0 m	4 m
North	2	2 m	5 m	7.2 m	2	1 m	3 m	1 m
West	15	1.7 m	5 m	4 m	2	1 m	3 m	1 m
South	2	2 m	5 m	7.2 m	3	1 m	2 m	1 m

Table 17 Final opening details

New warehouse lighting fixtures are auto-dimming, with a switch-off occupancy sensor "on" and "off". In other words, lighting fixtures automatically adjust the brightness to meet certain illumination requirements in the area, to keep the interior space bright enough for a safe working environment. Together with an occupancy sensor, more electricity can be saved for interior illumination when the occupancy rate is changed. When daylighting is sufficient, less artificial lighting is required, and vice versa. After changing the size of opening and adding shade devices to bring more appropriate daylighting into the warehouse space, the reduction of lighting load is significant. Not all lighting fixtures need to be turned on permanently, and not all the lighting fixtures need to be fully activated individually. The new, renovated warehouse lighting load is presented in Figure 73 and Table 18. Results also demonstrate that the illumination load after 12pm is lower than during the morning, which is due to the brightness of the daylighting. The sun reaches its peak height around 2pm which is also the brightest time of a day. More daylighting can come through the window and illuminate the interior space.

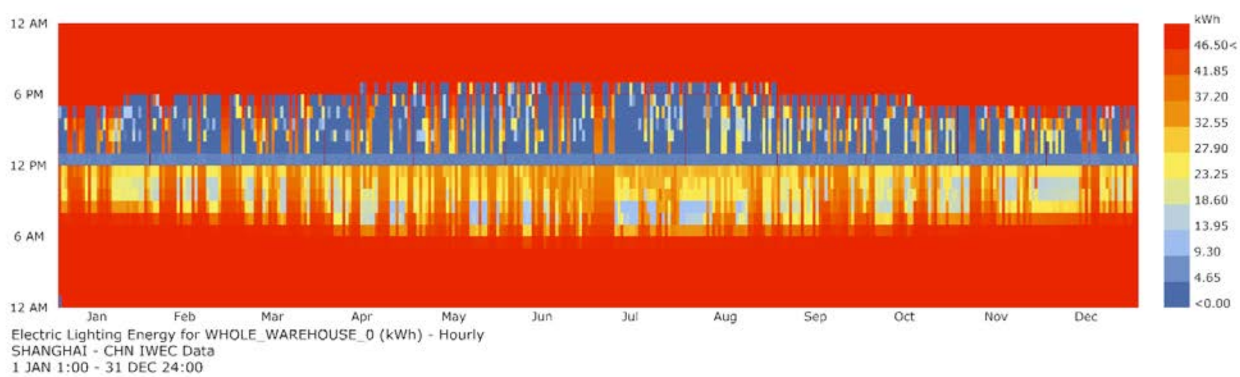


Figure 73 New Monthly E/L

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
KWh	27222	23433	26216	23327	24823	23155	23493	23133	24953	25522	25984	27264

Table 18 New Monthly E/L

However, the cooling load is increased, due to a higher window-to-wall ratio. The warehouse has more solar heat gain compared to the existing building design. The increased cooling load can be seen in Figure 74 and Table 19. The new highest cooling load is 489.51 kWh, which appears at the middle of a day.

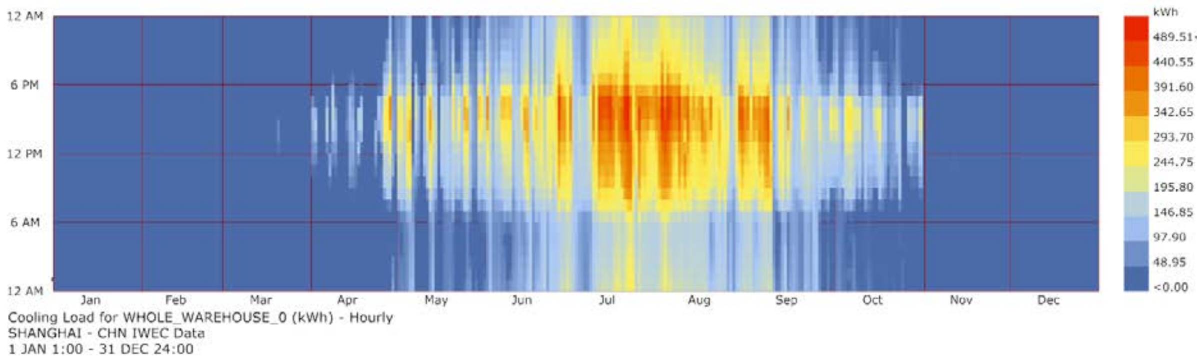


Figure 74 Cooling load of whole warehouse space (New)

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
kWh	0	0	0	9346	50421	98356	148091	141051	89945	29000	0	0

Table 19 Cooling load of whole warehouse space (new)

3. Strategy II: Passive cooling

The selected warehouse had to be separated into five different zones to run the cooling load analysis in this second passive cooling analysis section. This was because a separate controller is required for manual operation. The regional building HVAC system always turns on when the building is occupied during the hot season. The cooling set point is maintained at 22 °C for office space, and 18 °C for bulk space. To identify the improvement between the existing cooling load results and the new cooling load results, the cooling set point for the office and bulk areas remains the same.

There are three steps regarding passive solutions to approach cooling energy reduction. These are reducing total solar heat gain by adding appropriate shading devices, resetting a suitable HVAC operation schedule, and establishing appropriate timings for opening fenestration for air exchange.

1. Step 1: Cut down the solar heat gain

Two unitized shading devices are added to each existing window and located at the top edge of each window. The depth of each shading device is 0.5 m, and the distance between the two devices is also 0.5 m.

1.1. Zone A Area

a. Warehouse - Zone A - Office space solar heat gain (New)

Four shading devices are added to the existing windows in zone A office space, as presented in Figure 75. The new zone A office space solar heat gain is indicated in Figure 76 and Table 20. The reduction in total heat gain is a small amount because zone A office space has a small floor area.

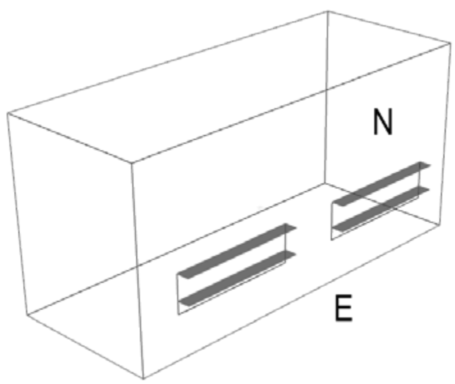


Figure 75 Zone A office space shading devices

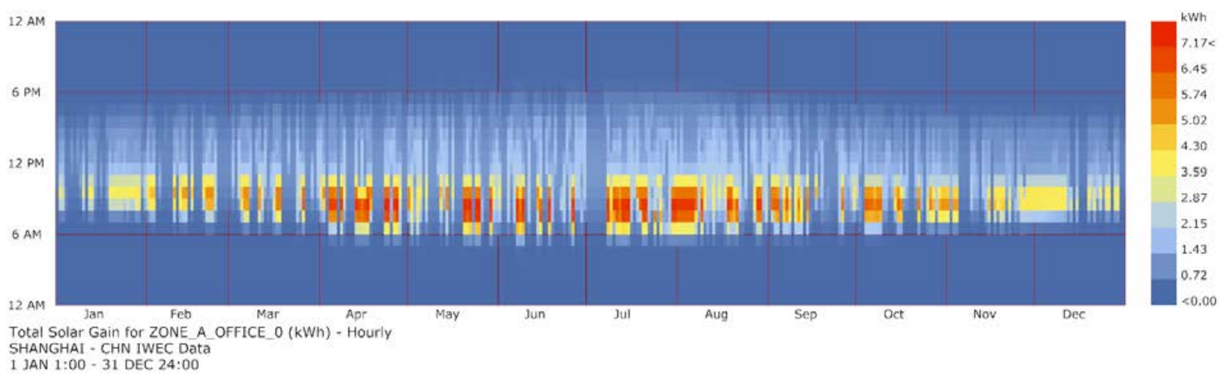


Figure 76 Zone A office space solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	293	307	373	574	536	497	651	688	440	471	347	331

Table 20 Zone A office space solar heat gain (New)

b. Warehouse - Zone A - Bulk space solar heat gain (New)

Eight shading devices are added to the existing windows in zone A bulk space, as illustrated in Figure 77. The new zone A bulk space solar heat gain is presented in Figure 78 and Table 21. Once the shading devices are added, the reduction of total heat gain is significant because the existing windows are located on the south side.

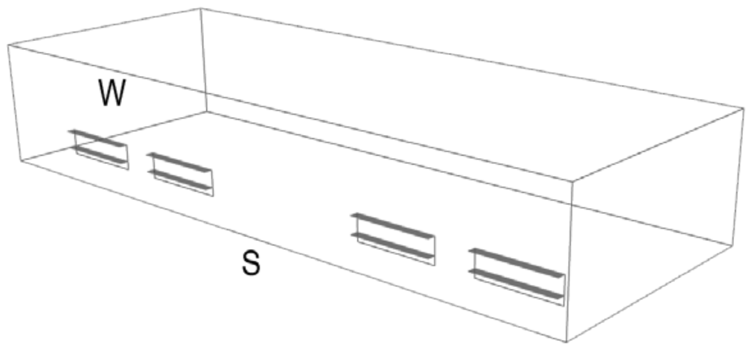


Figure 77 Zone A bulk space shading devices

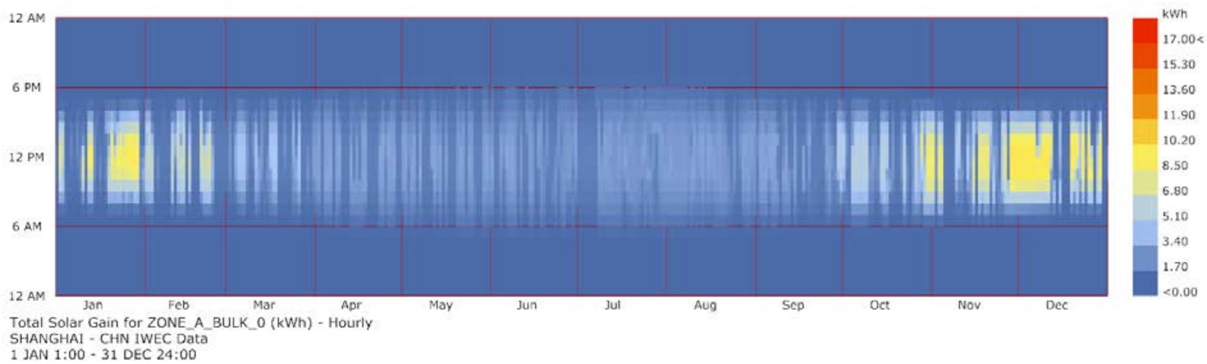


Figure 78 Zone A bulk space solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	781	542	444	444	470	462	515	561	431	749	870	1077

Table 21 Zone A bulk space solar heat gain (New)

1.2. Zone C Area

a. Warehouse - Zone C - Office space solar heat gain (New)

Two shading devices are added to the existing window in zone C office space, as shown in Figure 79. The new zone C office space solar heat gain is shown in Figure 76 and Table 20. The reduction of total heat gain is a small amount due to the small floor area.

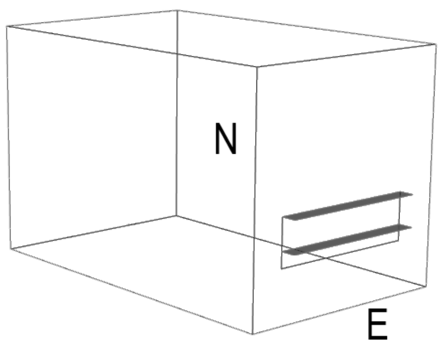


Figure 79 Zone C office space shading devices

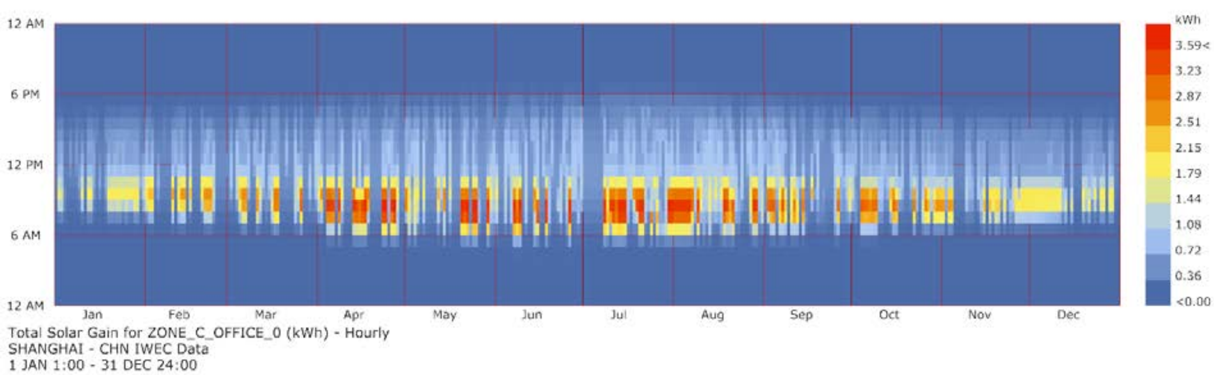


Figure 80 Zone C office space solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	147	154	187	288	269	250	327	346	221	237	174	163

Table 22 Zone C office space solar heat gain (New)

b. Warehouse - Zone C - Bulk space1 solar heat gain (New)

Two shading devices are added to the existing window in zone C bulk space 1, as shown in Figure 81. The new zone C bulk space 1 solar heat gain is presented in Figure 82 and Table 23. Here, the reduction of total heat gain is a small amount.

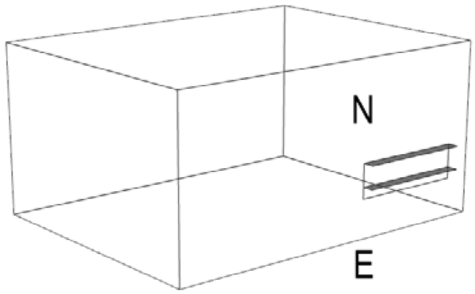


Figure 81 Zone C bulk space1 shading devices

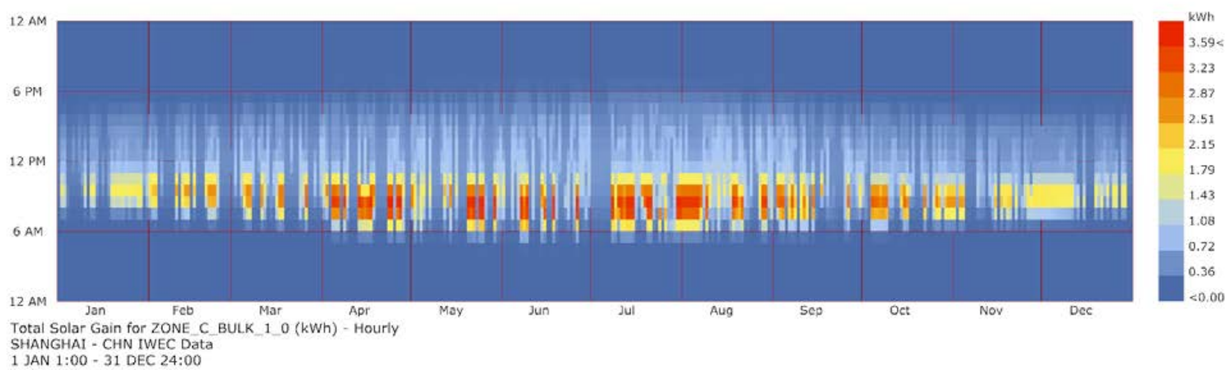


Figure 82 Zone C bulk space1 solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	146	153	186	287	268	249	326	344	220	235	173	165

Table 23 Zone C bulk space solar heat gain (New)

c. Warehouse - Zone C - Bulk space2 solar heat gain (New)

N/A

1.3. Zone E Area

a. Warehouse - Zone E - Office space solar heat gain

Four shading devices are added to the existing windows for zone E office space, as shown in Figure 83. The new zone E office space solar heat gain results are very similar to those for zone A office space, because both areas have the same floor area and window size. Results are presented in Figure 84 and Table 24. The reduction of total heat gain is not significant.

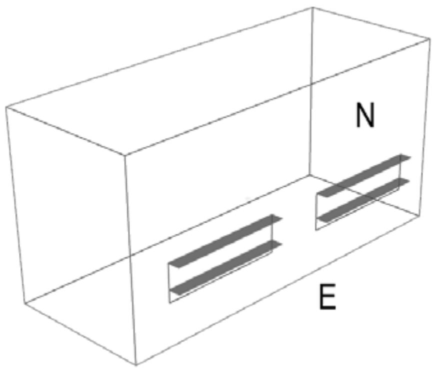


Figure 83 Zone E office space shading devices

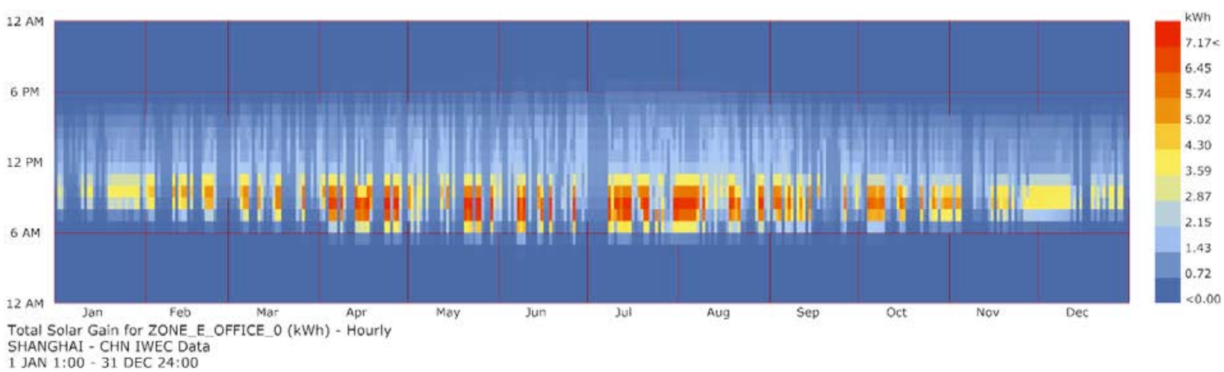


Figure 84 Zone E office space solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	293	307	373	576	536	498	651	685	440	470	348	332

Table 24 Zone E office space solar heat gain (New)

b. Warehouse - Zone E - Bulk space solar heat gain

Eight shading devices are added to the existing windows for zone E bulk space, as shown as Figure 85. Although zones A and E bulk spaces have the same total floor area and the same size windows, the total heat gain is entirely different. The windows in zone E face north, which has much less solar heat. The new zone E bulk space solar heat gain is shown in Figure 78 and Table 21 Figure 76. The reduction of total heat gain is not significant after adding the shade device, because there is little increase in solar heat gain regionally.

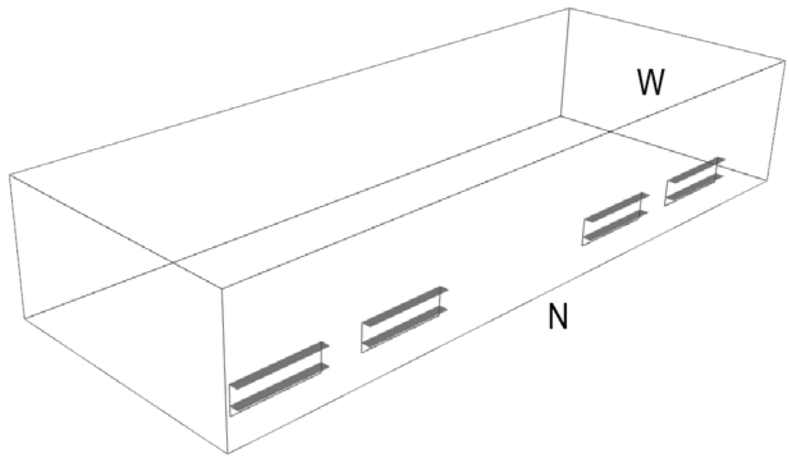


Figure 85 Zone E bulk space shading devices

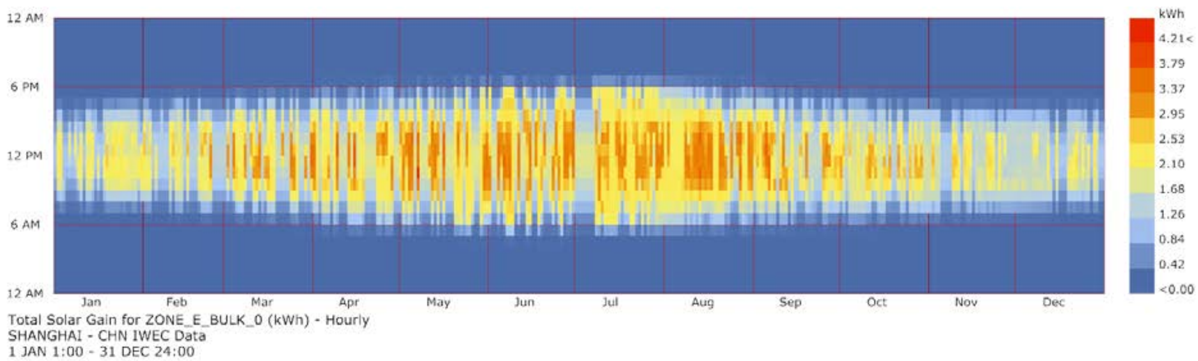


Figure 86 Zone E bulk space solar heat gain (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	351	337	491	463	669	711	756	742	527	472	368	325

Table 25 Zone E bulk space solar heat gain (New)

2. Step 2: New cooling schedule

There are some factors that should be included in the new the cooling schedule. Different building type, different occupancy schedule, different number of people per area, and different occupancy activity can affect the HVAC system significantly. It should be noted that the cooling set point remains as the existing setting, as mentioned previously. The cooling temperature is 22 °C constantly for the office space during the hot season, and 18 °C for the bulk space.

a. Warehouse bulk space occupancy rate

Table 26 presents the details of the daily occupancy rate for warehouse-bulk spaces A and E as a percentage from Monday to Sunday. There are 30 employees working in one warehouse-bulk space, which is divided into two groups: daytime and night time. The daytime group has 20 team members, while the night time group has 10 team members. The daytime group office hours are from 8 am to 8 pm and the night time group works from 9 pm to 7 am. The daytime group occupancy percentage is 0.66 (20/30 = 0.66), and the night time group building occupancy percentage is 0.33 (10/30 = 0.33). However, at 12 pm it is assumed that only 5 people stay without taking a lunch break, and therefore the warehouse-bulk space occupancy rate should be 0.17 (5/30 = 0.166).

Warehouse A&E	**0:00 am - 07:00 am**	**8:00 am - 11:00 am**	**12:00 pm**	**13:00 pm - 20:00 pm**	**21:00 pm- 23:00 pm**
Occupancy rate	0.33	0.66	0.17	0.66	0.33

Table 26 Zone A and Zone E warehouse-bulk occupancy rate

Table 27 presents the occupancy rate for zone C warehouse-bulk space. It should be notes that zone C warehouse has to be separated into areas 1 and 2. There are 30 employees in total, with 20 in the daytime group and 10 in the night time group. The 30 employees are divided evenly to simplify the calculation, thus: 10 people in each area for the daytime group and 5 people in each area for the night time group. The only difference is the occupancy rate during lunch time, which should be 0.2 (3/15 = 0.2).

Warehouse C	**0:00 am - 07:00 am**	**8:00 am - 11:00 am**	**12:00 pm**	**13:00 pm - 20:00 pm**	**21:00 pm- 23:00 pm**
Occupancy rate	**0.33**	**0.66**	**0.2**	**0.66**	**0.33**

Table 27 Zone C warehouse-bulk occupancy rate

b. Warehouse office space occupancy rate

Table 28 presents the weekday occupancy rate for offices A and E, from Monday to Friday, and Table 29 presents the weekday occupancy rate for office C. There are 6 people working in both office A and office E. There are 4 people working in office C. The office hours are from 8 am to 4 pm, and the office occupancy percentage is 100%. However, during lunch time only 2 people remain in the office space. Therefore, the office occupancy percentage for A and C is reduced to 0.33 (2/6 = 0.33), while the office occupancy percentage for B is reduced to 0.5 (2/4 = 0.5).

Weekday Office A & E	**0:00 am- 7:00 am**	**8:00 am - 11:00 am**	**12:00 pm**	**13:00 pm- 18:00 pm**	**19:00 pm- 23:00pm**
Occupancy rate	0	1	0.33	1	0

Table 28 Office A&E occupancy rate (weekday)

Weekday Office C	**0:00 am- 7:00 am**	**8:00 am - 11:00am**	**12:00 pm**	**13:00 pm- 18:00 pm**	**19:00 pm- 23:00pm**
Occupancy rate	0	1	0.5	1	0

Table 29 Office C occupancy rate (weekday)

Table 30 presents the weekend occupancy rates for offices A and E, whilst Table 31 shows the weekend occupancy rate for office C. During the weekend, only two people are required in each office space. The occupancy percentage for offices A and E is 0.33 (2/6 = 0.33). The occupancy percentage for office C is 0.5 (2/4 = 0.5). During lunch time, the office occupancy percentage for offices A and C will reduce to 0.17 (1/6 = 0.167), while B office occupancy percentage is reduced to 0.25 (1/4 = 0.25).

Weekend Office A & E	0:00 am-7:00 am	8:00 am - 11:00am	12:00 pm	13:00 pm-18:00 pm	19:00 pm-23:00pm
Occupancy rate	0	0.33	0.17	0.33	0

Table 30 office A& E occupancy rate (weekend)

Weekend Office C	0:00 am-7:00 am	8:00 am - 11:00am	12:00 pm	13:00 pm-18:00 pm	19:00 pm-23:00pm
Occupancy rate	0	0.5	0.25	0.5	0

Table 31 Office C occupancy rate (weekend)

c. Warehouse bulk space occupancy activity level

The occupancy activity level also is known as the metabolic rate, which is assumed as 1.8 for warehouse staff (a person's metabolic rate will be 1.8 met if he spends 30 minutes out of each hour lifting/packing, 15 minutes filing, 15 minutes standing, and 15 minutes walking around). However, an employee is not always fully engaged in heavy duty activities, and so the metabolic rate will not stay as the same. When a person is sitting, the metabolic rate reduces to 1. Met rate need to be transferred into W for calculation, where 1 met is equal to 120 W and 1.8 met is equal to 216 W. The results of warehouse-bulk space are presented in Table 32.

W ACE	0:00 am	1:00 am 3:00 am	4:00 am	5:00 am 11: 00 am	12:00 pm	13:00 pm 17:00 pm	18:00 pm	19:00 pm 23:00 pm
Met rate	120	216	120	216	120	216	120	216

Table 32 Warehouse A,C & E occupancy activity level

d. Warehouse office space occupancy activity level

A regular office worker’s met rate is around 1.1 equal to 132 W when they are typing and filing. The met rate drops to 1.0 (120 W) when they are only sitting. The results are presented in Table 33.

O ABC	**0:00 am 7:00 am**	**8:00 am 11:00am**	**12:00 pm**	**1:00 pm 6:00 pm**	**19:00 pm 23:00pm**
Met rate	0	132	120	132	0

Table 33 Office A,C& E occupancy activity level

e. Warehouse bulk space number of people per floor area

A large space with a high human density can have the same occupancy rate as a small space with a low human density. However, people can themselves also release heat into a space. Therefore, the number of people per area needs to be considered and calculated to determine the amount of heat that each person generates. Varying human density requires different settings for the cooling system. Zones A and E warehouse-bulk space floor area is 651 m^2. The total floor area of zone C warehouse-bulk space area is 1014 m^2, (including area 1, which is 186 m^2 and area 2, which is 828 m^2). The number of people per floor area of warehouse-bulk space for A and E is presented in Table 34.

Warehouse A&E	**0:00 am - 07:00 am**	**8:00 am - 11:00 am**	**12:00 pm**	**1:00 pm - 20:00 pm**	**21:00 pm- 23:00 pm**
Num. of People. Per Area	0.015	0.03	0.007	0.03	0.015

Table 34 Warehouse A & E number of people per floor area

The number of people per floor area for each area of warehouse-bulk space for C is presented in Table 35.

Warehouse C Area 1	0:00 am - 07:00 am	8:00 am - 11:00 am	12:00 pm	1:00 pm - 20:00 pm	21:00 pm- 23:00 pm
Num. of People. Per Area	0.02	0.053	0.016	0.053	0.02
Warehouse C Area 2	**0:00 am - 07:00 am**	**8:00 am - 11:00 am**	**12:00 pm**	**1:00 pm - 20:00 pm**	**21:00 pm- 23:00 pm**
Num. of People. Per Area	0.006	0.012	0.003	0.012	0.006

Table 35 Warehouse C1 & C2 number of people per floor area

f. Warehouse office space number of people per floor area

Zones A and E office space area is 93 m^2. Zone C office space area is 90 m^2. Weekday result of Zone A and Zone E are presented in Table 36 and the weekend results are presented in Table 37. Weekday result of Zone C are presented in Table 38 and the weekend results are presented in Table 39.

Zone A & E office （Weekday）	0:00 am - 07:00 am	8:00 am - 11:00 am	12:00 pm	1:00 pm - 20:00 pm	21:00 pm- 23:00 pm
Num. of People. Per Area	0.00	0.064	0.021	0.064	0.00

Table 36 Warehouse office space A & E number of people per floor area (weekday)

Zone A & E office (Weekend)	0:00 am - 07:00 am	8:00 am - 11:00 am	12:00 pm	1:00 pm - 20:00 pm	21:00 pm- 23:00 pm
Num. of People. Per Area	0.00	0.021	0.01	0.021	0.00

Table 37 Warehouse office space A & E number of people per floor area (weekend)

Zone C office (weekday)	0:00 am - 07:00 am	8:00 am - 11:00 am	12:00 pm	1:00 pm - 20:00 pm	21:00 pm- 23:00 pm
Num. of People. Per Area	0.00	0.044	0.022	0.044	0.00

Table 38 Warehouse office space C number of people per floor area (weekday)

Zone C office (weekend)	0:00 am - 07:00 am	8:00 am - 11:00 am	12:00 pm	1:00 pm - 20:00 pm	21:00 pm- 23:00 pm
Num. of People. Per Area	0.00	0.022	0.011	0.022	0.00

Table 39 Warehouse office space C number of people per floor area (weekend)

3. Step 3: Appropriate setting to operate fenestration

Once the exterior space air temperature is lower than the interior space, opening windows can help to reduce the interior temperature. This is generally referred to as natural ventilation. According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the minimum temperature for a traditional office space (without risk of heat exposure) is 20 °C and the maximum is 25.5 °C. According to the Approved Codes of Practice, the indoor temperature of a workplace should never be lower than 16 °C, unless the work involves a lot of physical activity; then the temperature can be as low as 13 °C. The existing cooling set point of the office area and the bulk area does not exceed these standards. The cooling set point will maintain 22 °C constantly for the office space, and 18 °C for the bulk space in the following cooling load analysis.

Details for natural ventilation setting are presented in Table 40. Having a minimum indoor temperature means that windows should remain closed when the indoor temperature is lower than the minimum indoor temperature setting. For instance, people do not usually want to open a window during winter time, because it is cold inside already. Utilizing the maximum indoor temperature requires that when the indoor temperature is higher than the set point, windows should be closed and the mechanical cooling system should be turned on. For instance, if the interior temperature becomes too high, then most likely the outdoor temperature is higher than that inside. At this point, it is necessary to rely on the HVAC system to help cool the space. The minimum outdoor temperature require the windows should be kept closed when the outside temperature is lower than the minimum outdoor temperature setting. It is not advisable to open windows if the outdoor temperature is too low. The maximum outdoor temperature requires that windows should be kept closed if the outside temperature is higher than maximum outdoor temperature. This can be understood as a night flushed strategy, which means windows are closed during daytime when the temperature is higher, and opened at night when the temperature drops. In this case, the warehouse bulk space is a 24-hours a day, 7-days a week service, a night flushed strategy can be extremely helpful in reducing the cooling load during the night. The percentage of glazed operable area is used to describe window's type. The window operable percentage can affect the total air flow volume and air exchange volume. The existing fenestration type is a single sliding window, so the total operable percentage is 50%. As mentioned previously, the 1.6 m/s wind speed is acceptable for warehouse bulk space, while 1 m/s is acceptable for office space.

	Office space	Warehouse space
Min indoor temperature	20℃	13℃
Max indoor temperature	25.5℃	18℃
Min outdoor temperature	22℃	22℃
Max outdoor temperature	26℃	26℃
Percentage of glaze operable area	50%℃	50%℃
Air speed	1m/s	1.6m/s

Table 40 Natural ventilation setting

4. Renovation summary of Strategy II

After adding shading devices to existing windows, resetting each zone to a new cooling schedule, and cooperating with natural ventilation at proper time, the total cooling load reduction is significant, especially for warehouse bulk space. The peak cooling load of office spaces still occurs at 7 am when the space is starting to be occupied. However, the peak cooling load of warehouse bulks space moves to the middle of the day. And the peak cooling load reduces as well. The cooling load only occurs from 7 am to 5 pm, which is exactly the time between sunrise and sunset. The remainder of the day's cooling load is extremely reduced by applying the night flush. The natural ventilation helps to reduce the interior space temperature by increasing air exchange and interior wind speed as mentioned early in research section.

A detailed analysis conclusion is in next final renovation summary section. The analysis data will be explained further.

1.1 Zone A Area

a. Warehouse - Zone A

The highest cooling load for the office space is reduced to 18.25 kWh, as presented in Figure 87 and Table 41. The highest cooling load for the bulk space is reduced to 47.64 kWh, as shown in Figure 88 and Table 42.

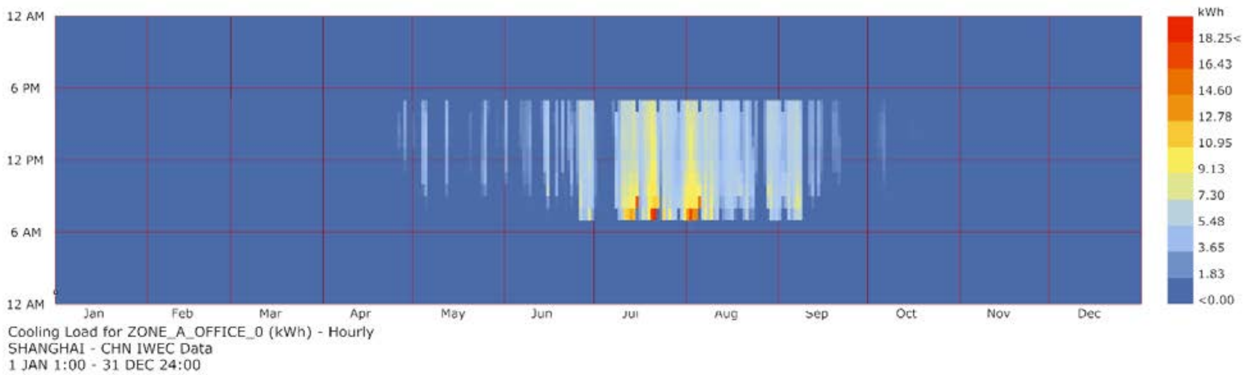


Figure 87 Zone A Office space cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	16	115	496	1556	1498	476	14	0	0

Table 41 Zone A office space cooling load (New)

b. Warehouse - Zone A - Bulk space cooling load (New)

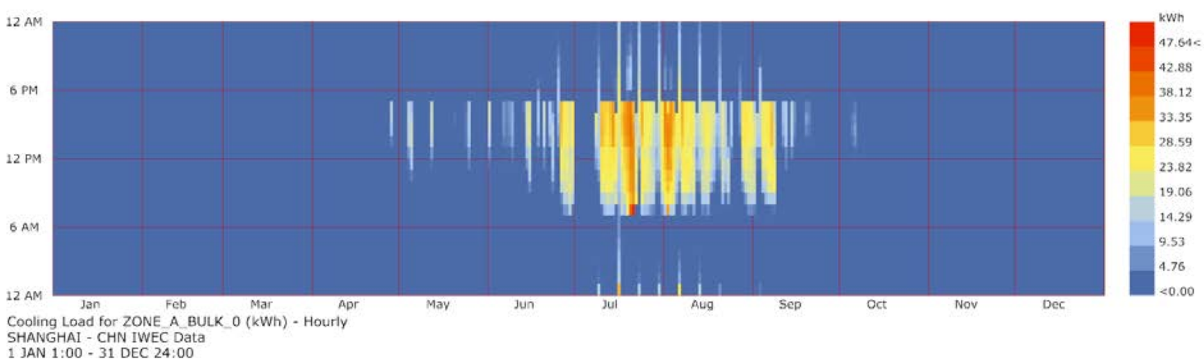


Figure 88 Zone Bulk space cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	40	282	1595	5225	4848	1405	26	0	0

Table 42 Zone Bulk space cooling load (New)

1.2 Zone C Area

a. Warehouse - Zone C

The highest cooling load for the office space is reduced to 14.75 kWh, as shown in Figure 89 and Table 43. The highest cooling load for bulk space1 is reduced to 12.06 kWh, as shown in Figure 90 and Table 44.

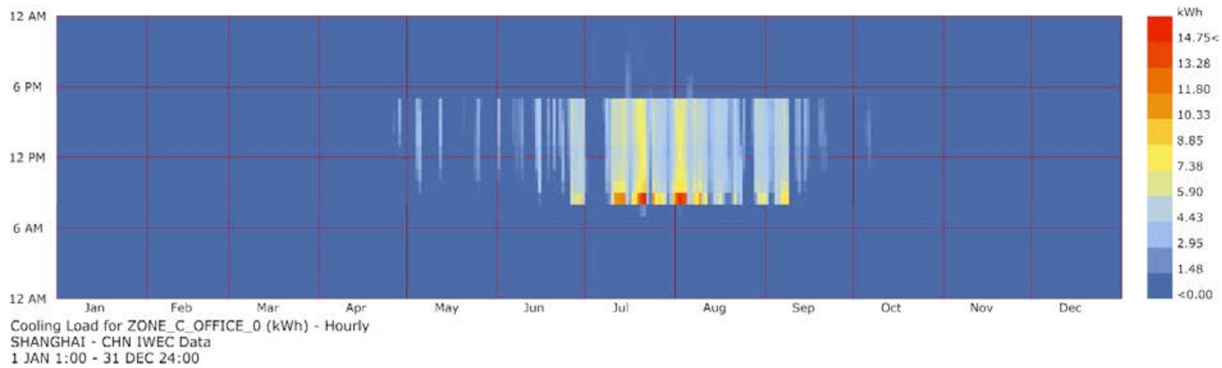


Figure 89 Zone C office cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	9	74	372	1291	1204	373	7	0	0

Table 43 Zone C office cooling load (New)

b. Warehouse - Zone C - Bulk space 1 cooling load (New)

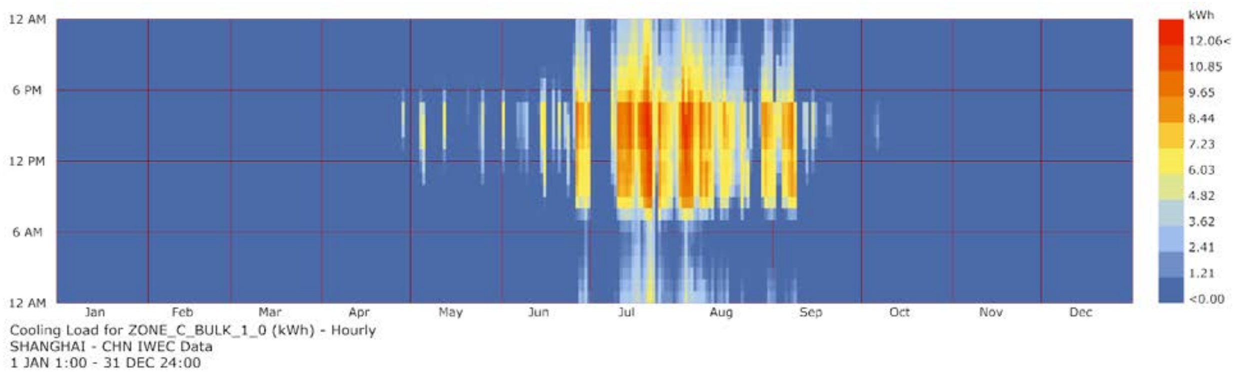


Figure 90 Zone C bulk space 1 cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	13	103	720	2580	2377	622	6	0	0

Table 44 Zone C bulk space 1 cooling load (New)

c. Warehouse - Zone C - Bulk space 2 cooling load (New)

After simply resetting the new cooling schedule, the highest cooling load for bulk space 2 is reduced to 43.92 kWh as shown in Figure 91 and Table 45.

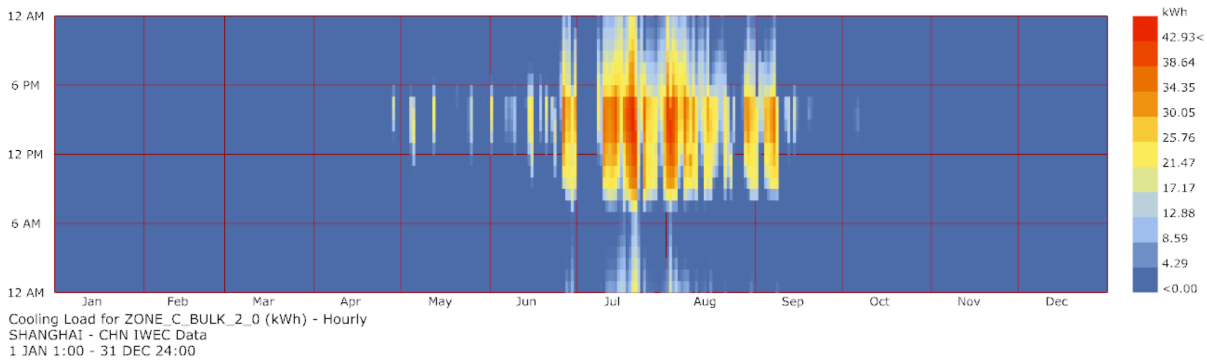


Figure 91 Zone C bulk space 2 cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	44	303	2159	7782	6912	1739	10	0	0

Table 45 Zone C bulk space 2 cooling load (New)

1.3 Zone E Area

a. Warehouse - Zone E

The highest cooling load for the office space is reduced to 17.76 kWh, as shown in Figure 92 and Table 46. The highest cooling load for the bulk space is reduced to 37 kWh, as shown in Figure 93 and Table 47.

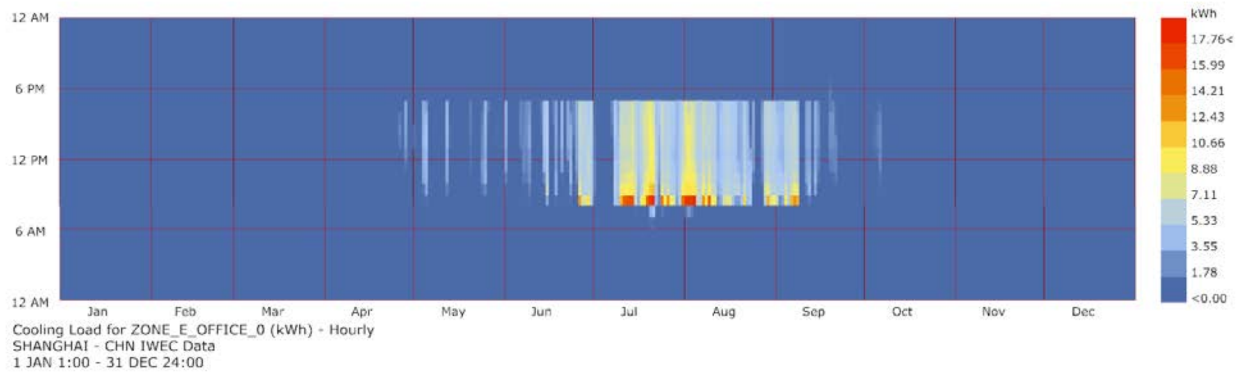


Figure 92 Zone E office space cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	16	114	493	1637	1543	486	12	0	0

Table 46 Zone E office space cooling load (New)

b. Warehouse - Zone E

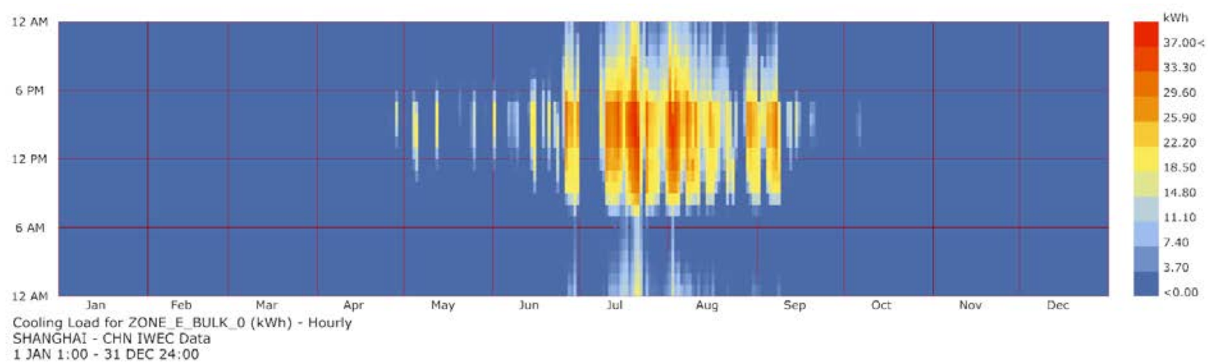


Figure 93 Zone E bulk space cooling load (New)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh	0	0	0	46	329	2150	7304	6570	1722	14	0	0

Table 47 Zone E bulk space cooling load (New)

VI. Final renovation summary

Increasing the total window-to-wall ratio allows more floor area to receive natural daylighting. Adding shading devices can help to block unwanted glazing and improve the quality of daylighting. This passive strategy does require changes to the building facade, however, the cost of construction is not included in the scope of this thesis.

1. Passive strategy I: Daylighting

1. Daylighting improvement

After applying a daylighting strategy, which increases the window-to-wall ratio and incorporates suitable shading devices, 55.4 % of the entire warehouse achieves the desired daylighting, which is between 100 and 2000 lux. Thus, the design goal of daylighting improvement has been accomplished. The total improvement percentage is 44.2%, which relates to 1 point of the LEED O+M: Existing Buildings V4 standard of daylight Option 1.

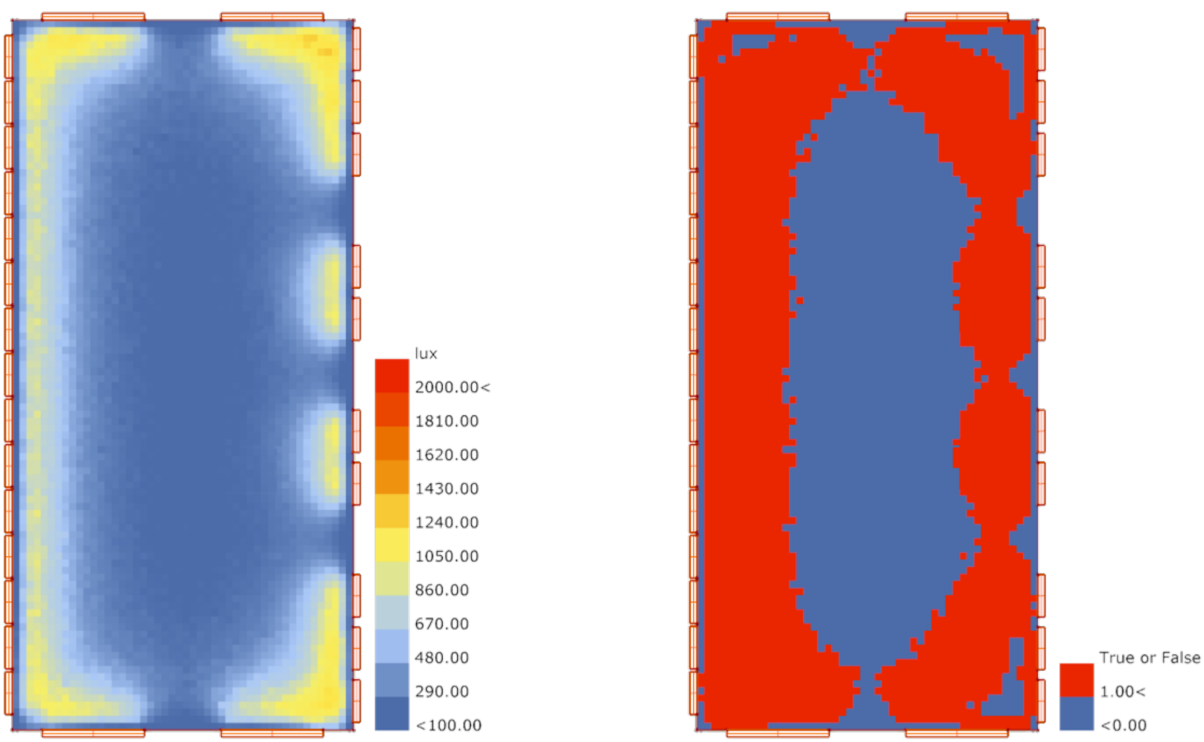
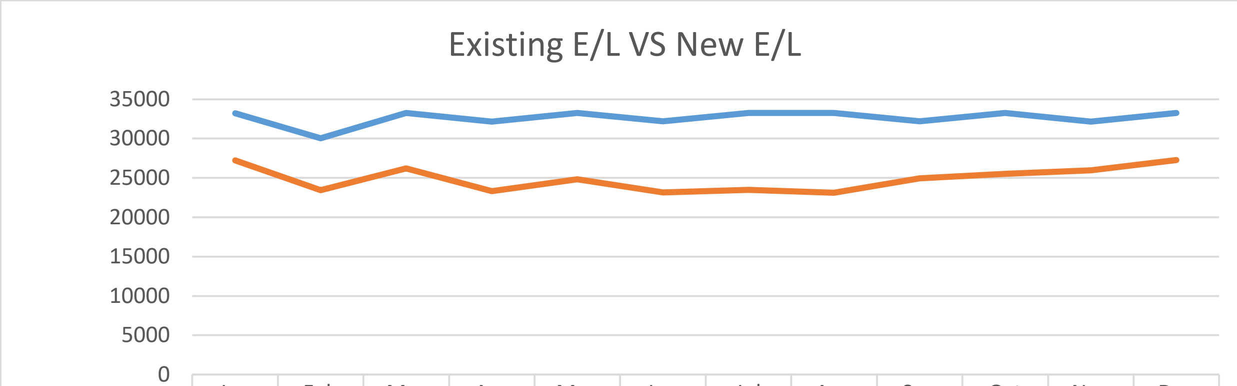


Figure 94 Final daylighting result

2. Reduction of electricity for illumination

More suitable daylighting can enter the building space after renovation. As a result, the illumination load is reduced. Comparing the existing electricity consumption for illumination to the new consumption for illumination, as shown in Figure 95, every month on average 7746.25 kWh can be saved. According to the management company, the price of 1 kWh in Shanghai is 1.3 RMB. Therefore, 10,070.125 RMB can be saved per month. The annual saving is therefore 120,841.5 RMB.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	33216	30038	33266	32173	33257	32195	33250	33243	32185	33239	32174	33244
New	27222	23433	26216	23327	24823	23155	23493	23133	24953	25522	25984	27264

Figure 95 Existing E/L VS New E/L

3. Increase of cooling load

The general cooling load is increased due to more heat gain, as the results in Figure 96 demonstrate. During the hot season (from April to October) the monthly increased cooling load is 6054 kWh. According to the management company, the price of 1 kWh in Shanghai is 1.3 RMB, therefore the total increased cost for the cooling load is 7870 RMB. Although the cooling load is increased, the increased cost is less than the amount saved. The final result is acceptable.

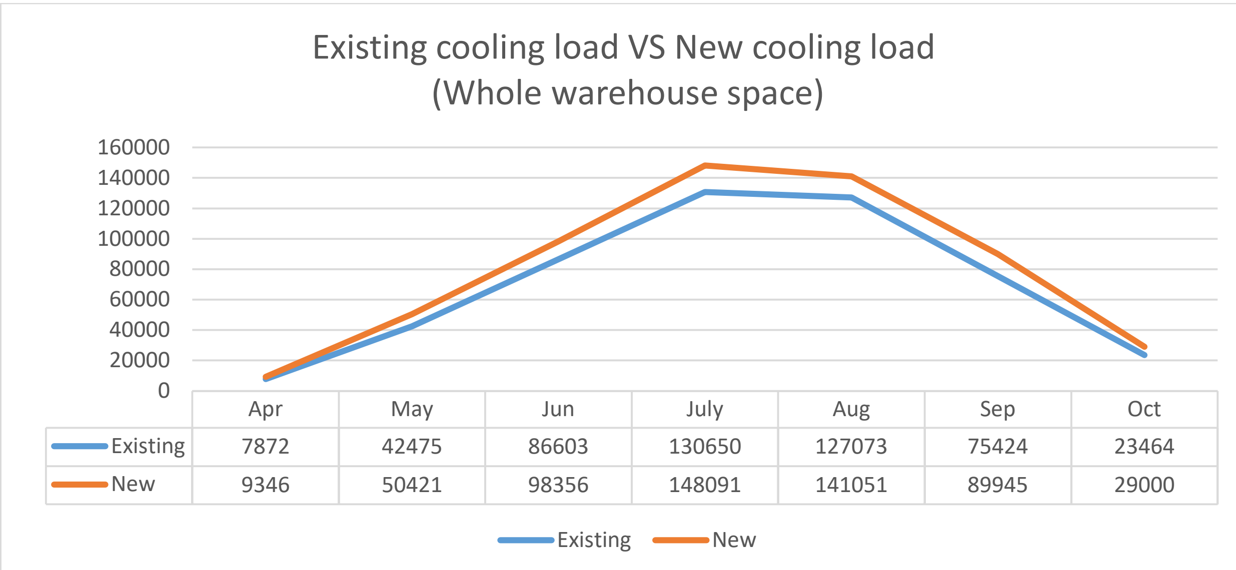


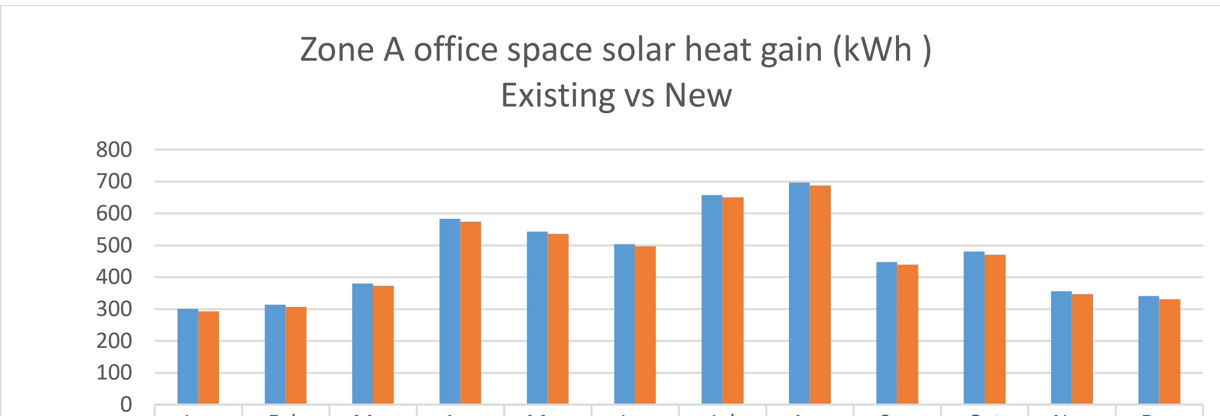
Figure 96 Existing Cooling Load of whole warehouse space VS New Cooling Load of whole warehouse space

2. Passive strategy II: Passive cooling

Direct solar heat gain can be easily blocked by installing shading devices to each window. Resetting the cooling schedule based on building type, cooling set point, occupancy schedule, number of people per area, and different occupancy activity levels can improve cooling efficiency. Natural ventilation and night flushing reduce the cooling energy significantly during the night when the warehouse is still occupied and regular warehouse activities continue. This passive strategy does not require any building envelope, and generates improvements with minimum cost.

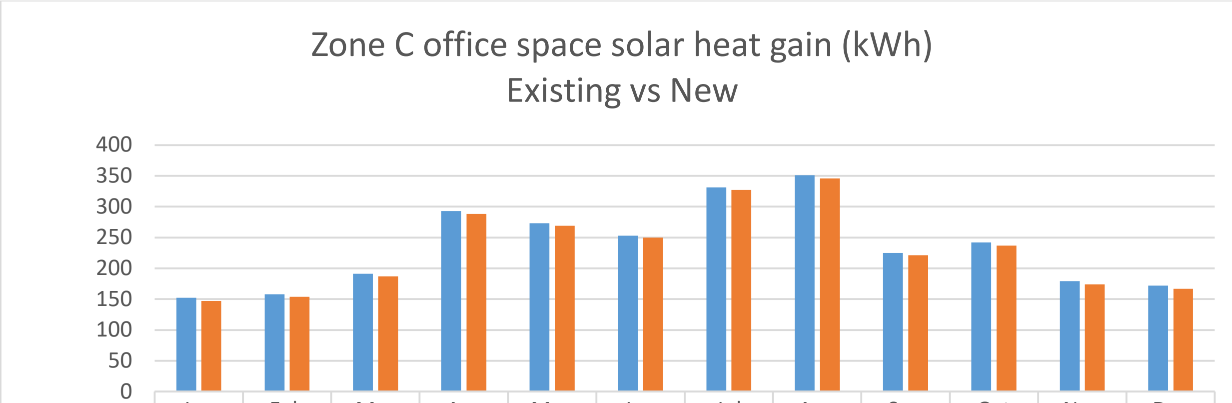
1. Total solar heat gain reduction

As Figure 97 and Figure 99 illustrate, 8.2 kWh of solar heat can be blocked every month on average, for zone A and E offices. Further, 4.42 kWh of solar heat can be blocked every month on average, for zone C office space, as illustrated in Figure 98.



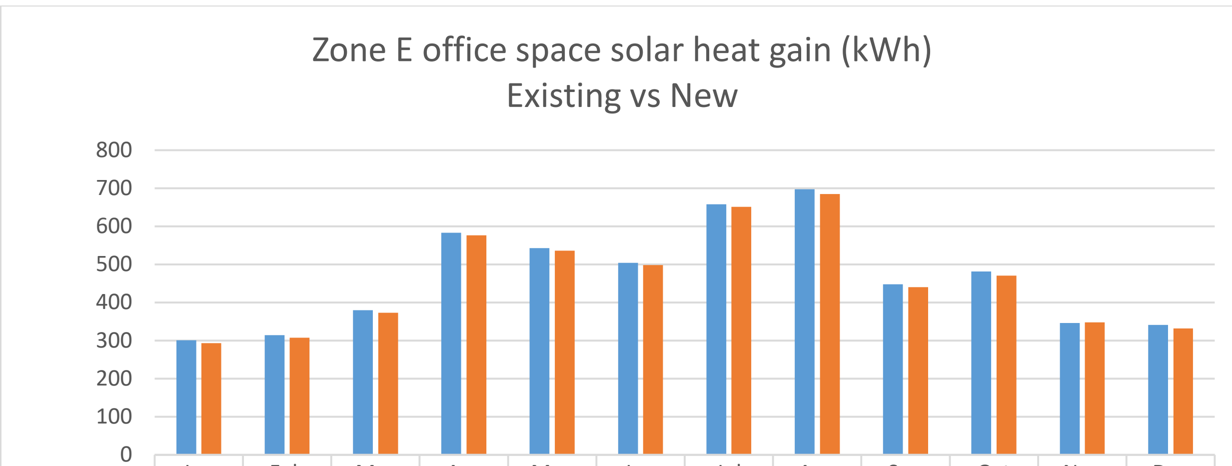
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	301	314	380	583	543	504	658	697	448	481	356	341
New	293	307	373	574	536	497	651	688	440	471	347	331

Figure 97 Zone A office space solar heat gain ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	152	158	191	293	273	253	331	351	225	242	179	172
New	147	154	187	288	269	250	327	346	221	237	174	167

Figure 98 Zone C office space solar heat gain ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	301	314	380	583	543	504	658	697	448	481	346	341
New	293	307	373	576	536	498	651	685	440	470	348	332

Figure 99 Zone E office space solar heat gain ex vs new

It is evident that 528.5 kWh solar heat can be blocked every month on average for zone A bulk space, as presented in Figure 100, whilst 3.83 kWh on average can be blocked for zone C bulk space1 (Figure 101) and 18.0 kWh on average for zone E bulk space (Figure 102).

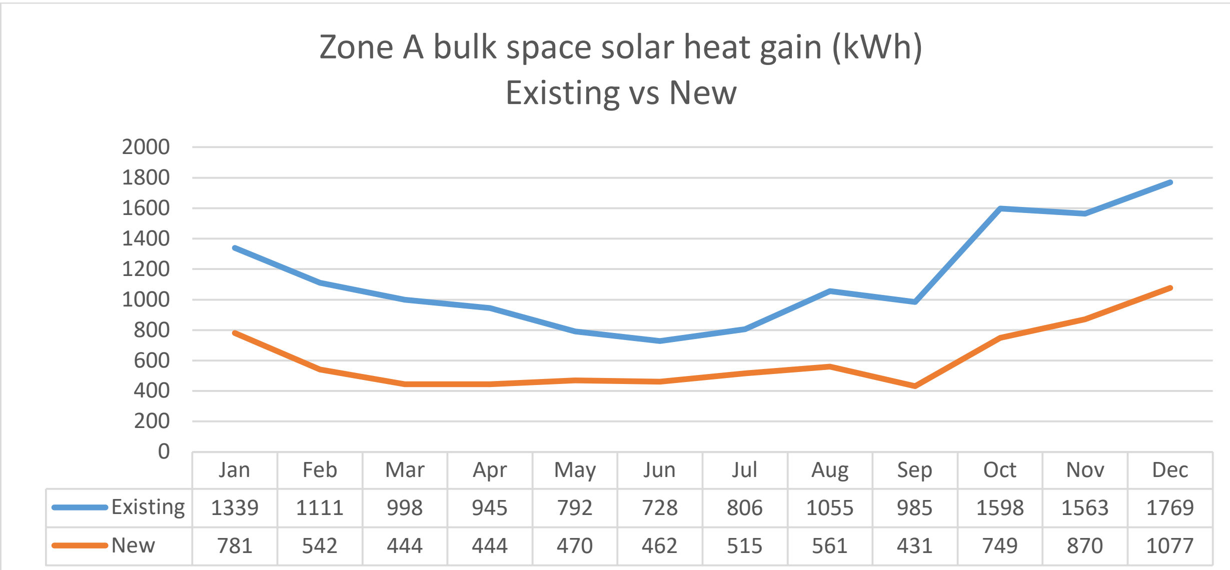


Figure 100 Zone A bulk space solar heat gain ex vs new

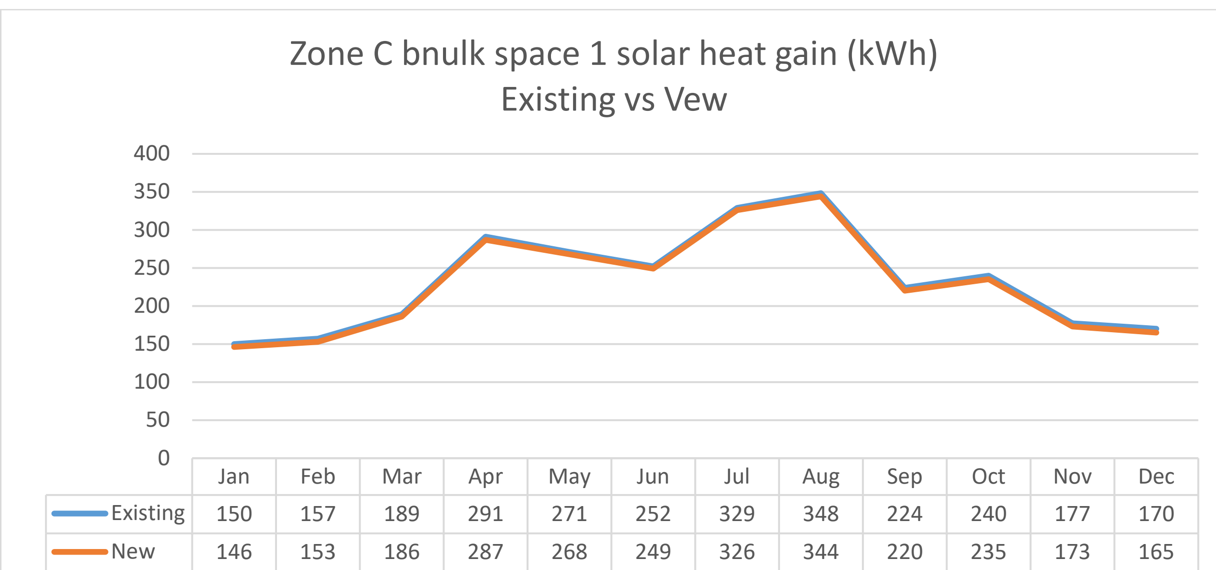
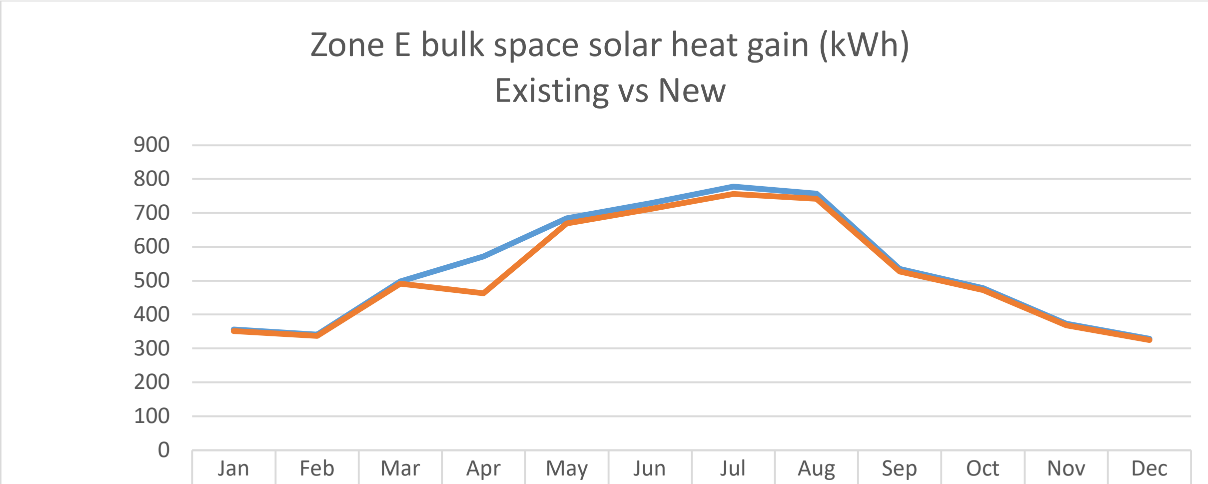


Figure 101 Zone C bulk space1 solar heat gain ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	356	341	498	572	684	728	778	757	535	478	373	329
New	351	337	491	463	669	711	756	742	527	472	368	325

Figure 102 Zone E bulk space solar heat gain ex vs new

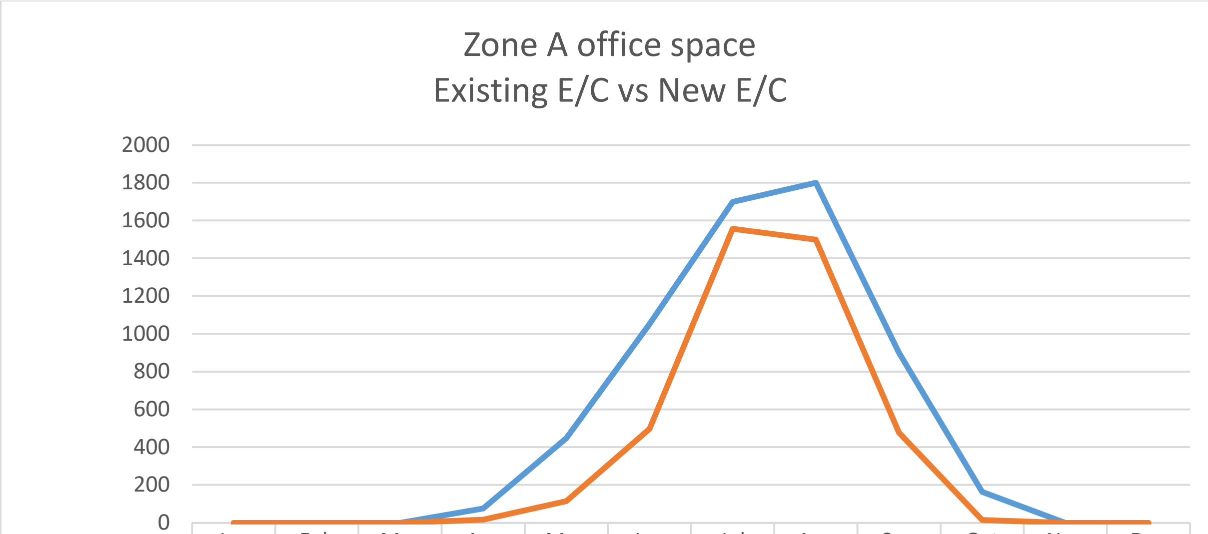
2. Total cooling load reduction

After resetting a new cooling operation schedule accurately, and establishing an appropriate time to open windows for air exchange with an acceptable temperature, (which is considered an action of natural ventilation), the cooling load can be significantly reduced. Thus, 20% cooling load reduction is achieved. Natural ventilation achieves a huge improvement in cooling load reduction. This action also attains to the prerequisite credits of LEED O+M: Existing building V4 Minimum indoor air quality performance.

Office space results are shown in Figure 103 to Figure 105.

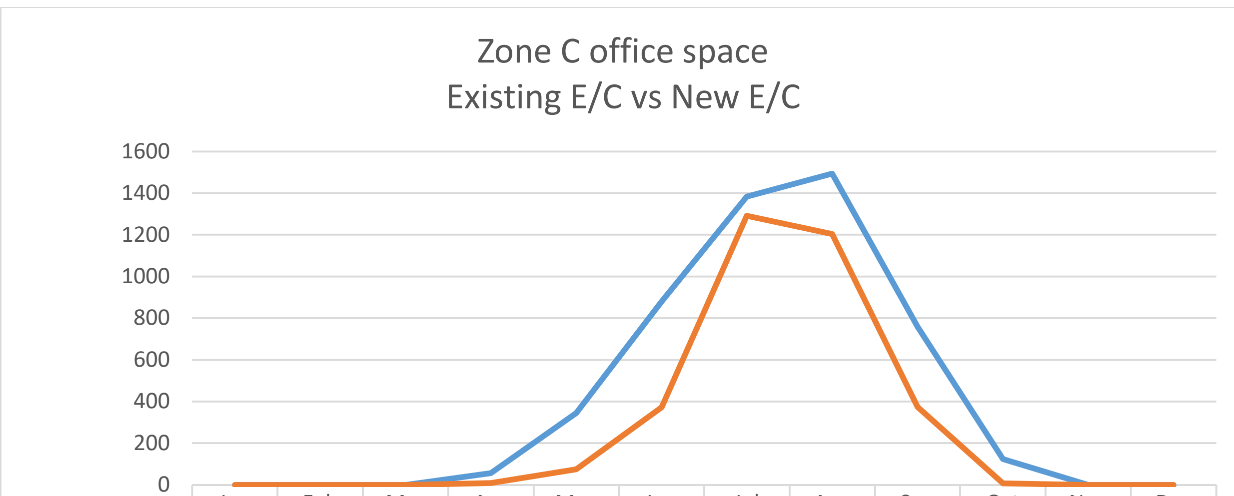
Has been established that 280.7 kWh can be saved monthly for zone A office space, 244 kWh can be saved monthly for zone C office space, and 264 kWh can be saved monthly for zone E office space.

According to the management company, the price of 1 kWh in Shanghai is 1.3 RMB. As a result, 364.91 RMB can be saved per month for zone A office space resulting in an annual saving of 2554.37 RMB. 447.2 RMB can be saved per month for zone C office space with an annual saving of 3130.4 RMB, and 343.2 RMB can be saved per month for zone E office space with an annual saving of 2402.4 RMB.



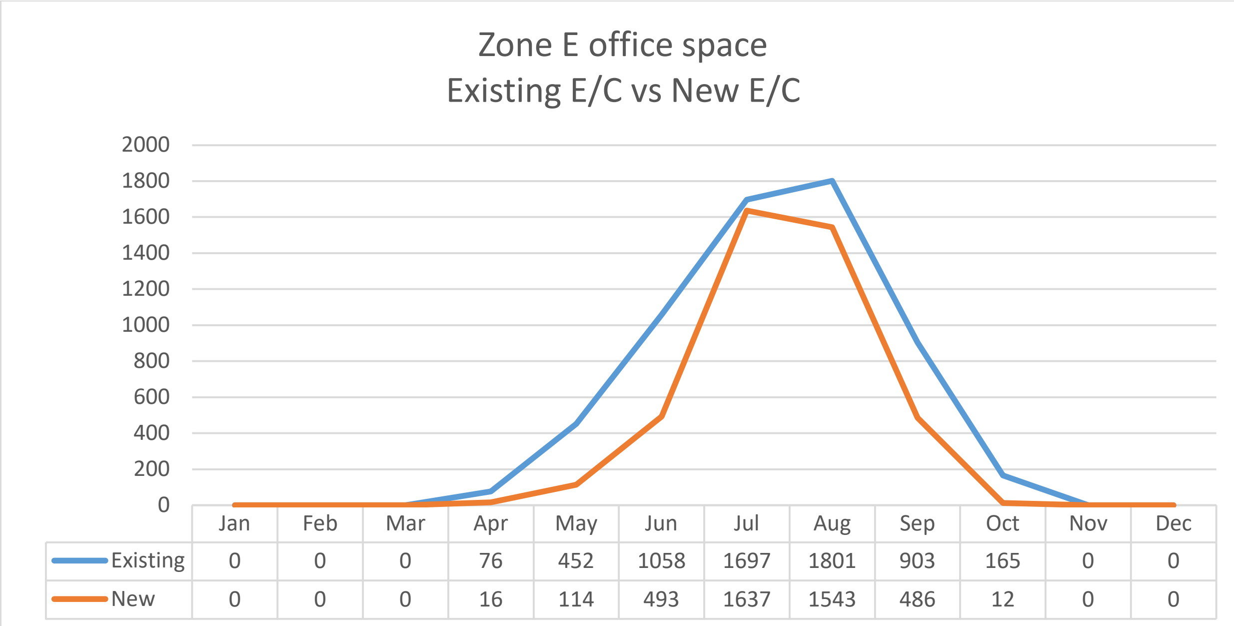
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	75	448	1052	1698	1800	900	163	0	0
New	0	0	0	16	115	496	1556	1498	476	14	0	0

Figure 103 Zone A office space cooling load ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	55.6	344.9	879.7	1383.5	1493.6	758.2	123.2	0	0
New	0	0	0	9	74	372	1291	1204	373	7	0	0

Figure 104 Zone C office space cooling load ex vs new



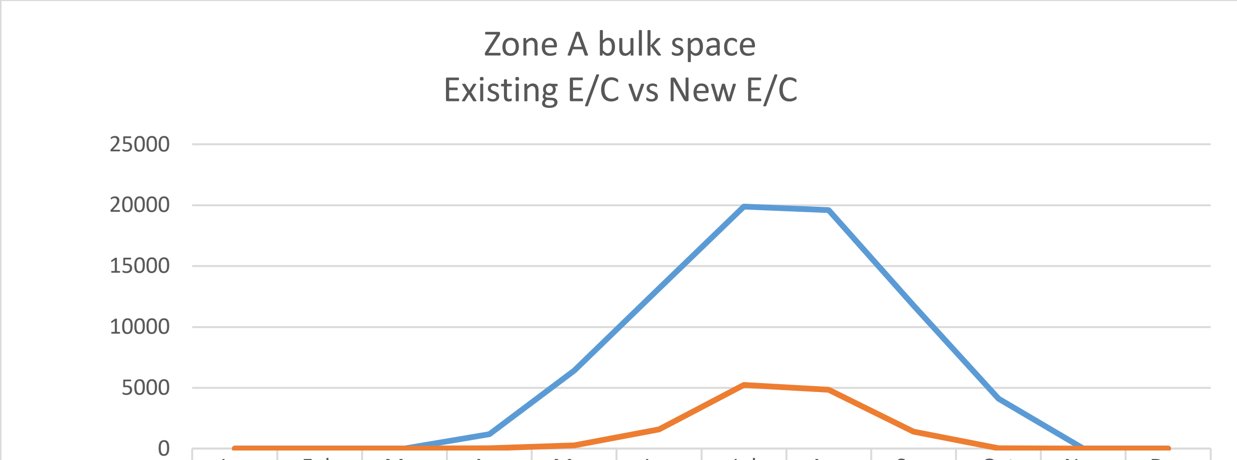
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	76	452	1058	1697	1801	903	165	0	0
New	0	0	0	16	114	493	1637	1543	486	12	0	0

Figure 105 Zone E office space cooling load ex vs new

The bulk space results are shown in Figure 106 to Figure 109.

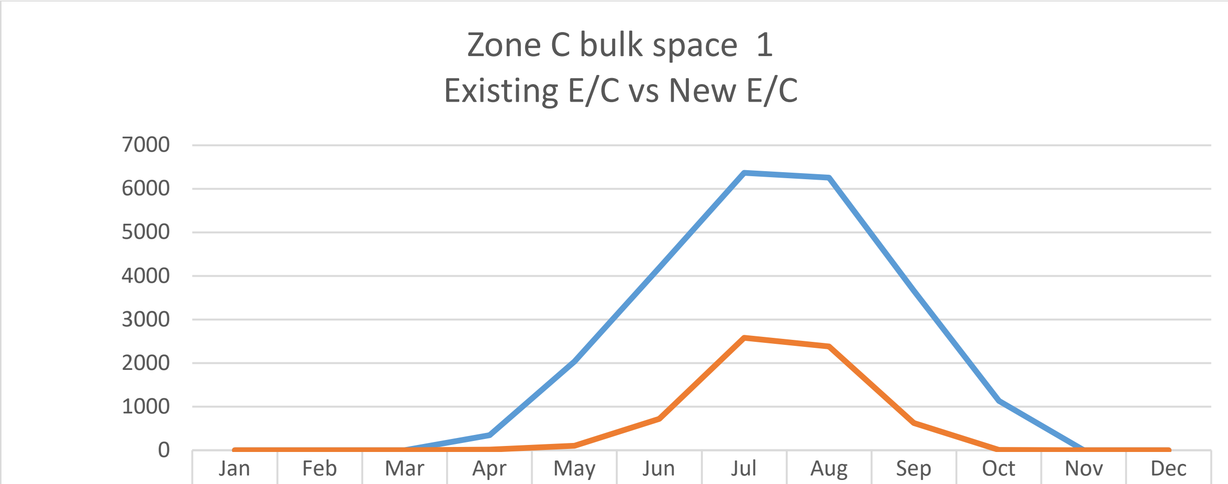
It has been established that 8959.7 kWh can be saved monthly for zone A bulk space, 2078.7 kWh can be saved monthly for zone C bulk space 1, and 9830.2 kWh can be saved monthly for zone C bulk space 2. Further, 7885 kWh can be saved monthly for zone E bulk space.

According to the management company, the price of 1 kWh in Shanghai is 1.3 RMB. As a result, 11,647 RMB can be saved per month for zone A bulk space, with an annual saving of 81,533.27 RMB. 2,702.3 RMB can be saved per month for zone C bulk space 1 and 12,779 RMB can be saved per month for zone C bulk space 2, providing a total annual saving of 112,271.12 RMB, and finally 10,250.5 RMB can be saved per month for zone E bulk space with an annual saving of 71,753.5 RMB.



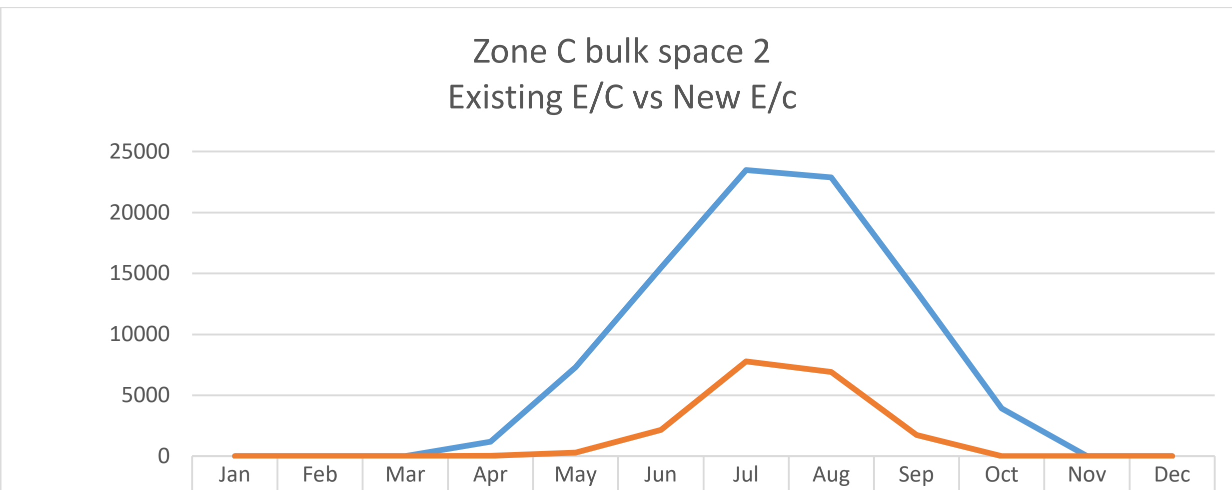
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	1186	6413	13173	19900	19595	11767	4105	0	0
New	0	0	0	40	282	1595	5225	4848	1405	26	0	0

Figure 106 Zone A bulk space cooling load ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	343	2030.9	4185	6365.3	6257	3661	1129	0	0
New	0	0	0	13	103	720	2580	2377	622	6	0	0

Figure 107 Zone C bulk space 1 cooling load ex vs new



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Existing	0	0	0	1197.9	7302	15474	23477.8	22882.5	13500	3927	0	0
New	0	0	0	44	303	2159	7782	6912	1739	10	0	0

Figure 108 Zone C bulk space 2 cooling load ex vs new

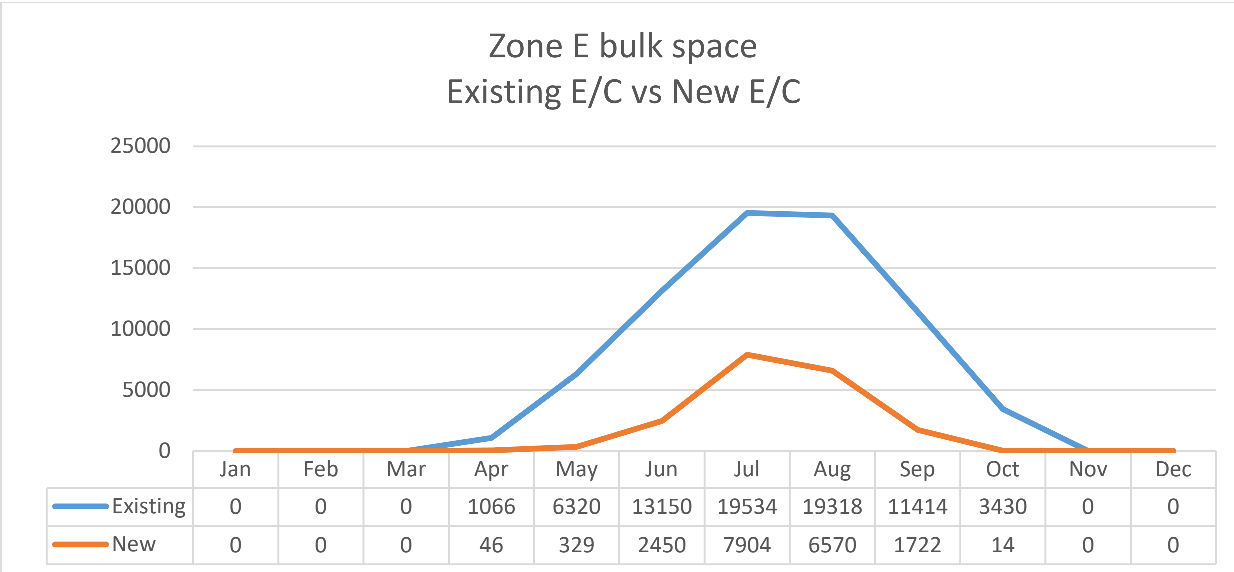


Figure 109 Zone E bulk space cooling load ex vs new

3. Reduction of daylighting

The second renovated 3D modeling is presented in Figure 110. Adding shading devices to existing windows does not have a significant influence on daylighting illumination. Compared to existing conditions, 10.2% of floor area receives appropriate daylighting, as the results in Figure 111 indicate.

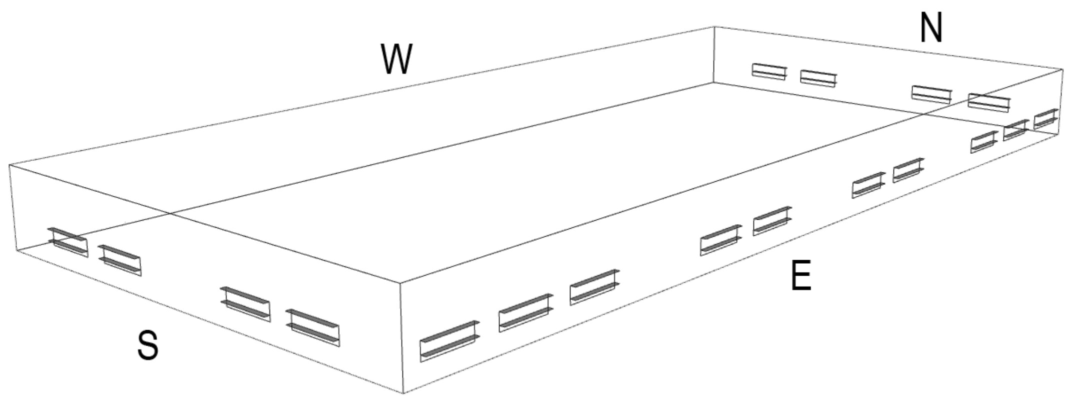


Figure 110 Second renovated 3D modeling

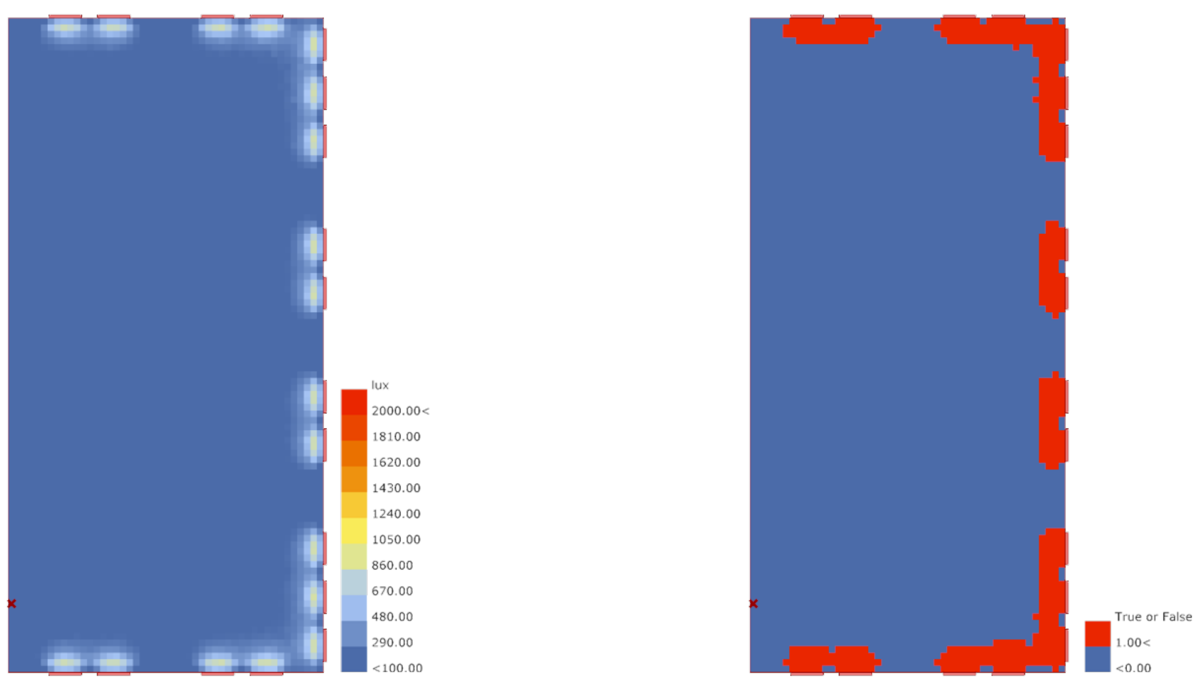


Figure 111 Daylighting result (New)

3. Working environment improvement

It is hard to measure the success of the working environment improvements, because the renovation has not actually been built. However, there are some metrics that can be used to demonstrate improvement. For this study, LEED O+M: Existing Buildings V4 is applied to determine the success. There are different catalogs included in LEED certification credits library. These specify the energy usage of buildings, its impact on environment, and on human health.

The daylighting strategy achieved 1 point of LEED V4 standard of daylight Option 1, by increasing the window-to-wall ratio and incorporating appropriate shading devices. The passive cooling strategy provides monitoring of mechanical ventilation (with a mixed-mode natural ventilation) when the mechanical ventilation is inactive, which is a prerequisite credits if an existing building is able to achieve LEED certification. Both the passive strategies investigated in this paper meet the LEED requirement, which is a universal, sustainable design standard applied globally.

A new psychrometric chart is generated after applying two passive strategies. Reducing direct solar heat gain by adding shading devices is considered one solution of thermal mass, while reducing the cooling load by finding an appropriate time to operate fenestration is considered as natural ventilation.

Figure 112 presents a new psychrometric chart for workers in the bulk space after applying both thermal mass strategy and natural ventilation incorporated with a night flushed strategy. The highlighted part I refers to the existing condition, while the highlighted part II is the added on area. As is evident from the figure, 36.5% of the entire year is the time that the workers can work in a comfortable environment. Thus, the improvement is 10.4%.

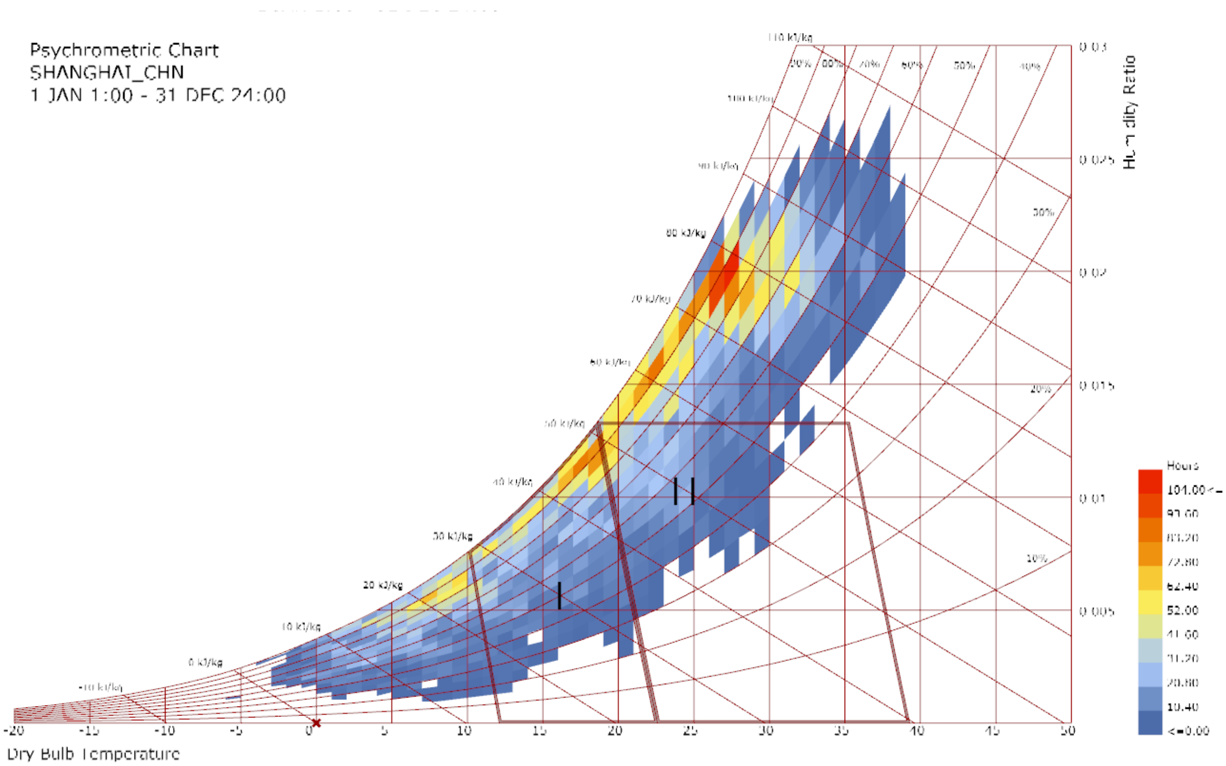


Figure 112 Psychrometric Chart of labors in warehouse-bulk space (New)

Figure 113 presents a new psychrometric chart for office staff in the office space. The highlighted part III is the existing condition, while the highlight part IV is the added on area. Thus, 29.8% of the entire year is the time that the workers can work in a comfortable environment, which means that the improvement is 6.8%.

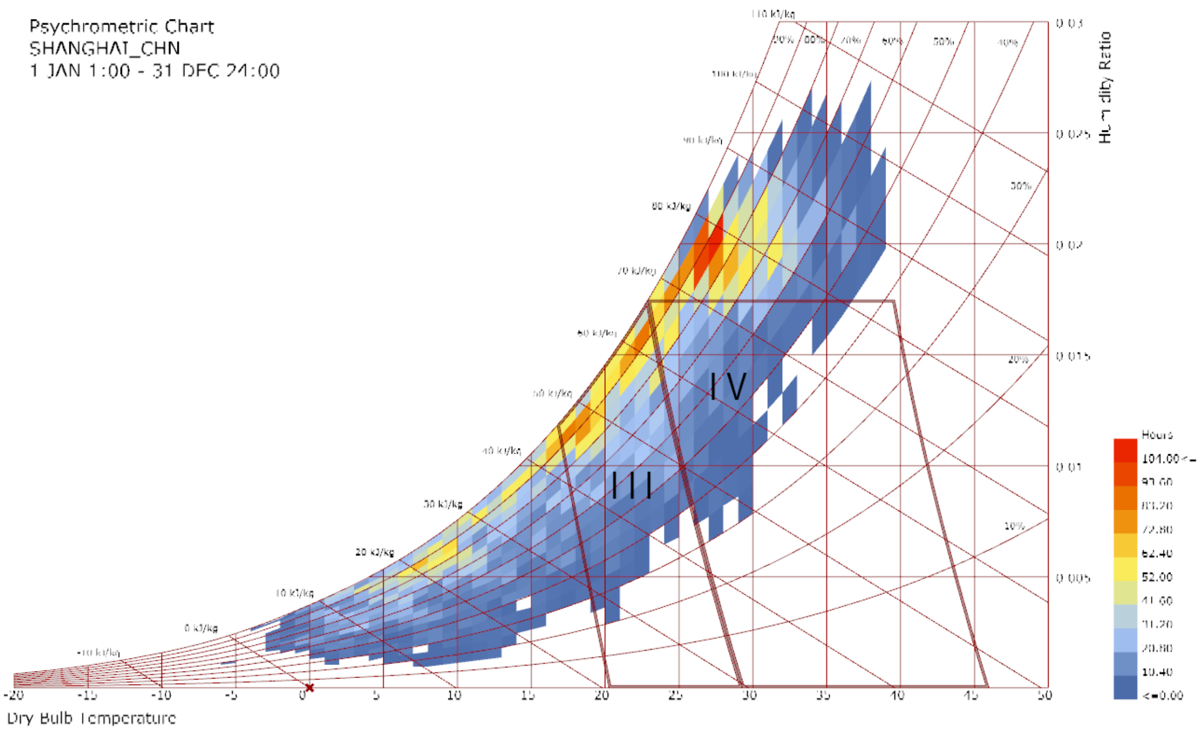


Figure 113 Psychrometric Chart of office staff in warehouse office space (New)

VII. Conclusion

"Triple bottom line" is a very important concept for sustainable design. A good sustainable design should create benefits at an environmental, social, and economic level. In this paper, two passive design strategies (daylighting and passive cooling) were investigated separately. The simulation-based new energy consumption indicated a large improvement from both an energy standpoint and a working environment standpoint. These two passive strategies help to reduce the usage of traditional energy resources, which is good for the environment; increases energy efficiency, which has an economic benefit; and improves the working environment, which is good for employees health. Instead of rebuilding entire industrial buildings, renovating existing industrial buildings, by applying passive strategies, holds a huge potential to save energy and improve the working environment. Further, improving existing building performance is a large part of sustainable architecture.

Each of these two passive strategies achieved significant improvements, based on the final analysis results. However, each passive strategy has its own negative impact on the existing warehouse. A decision should be made by the management company whether they want to reduce more illumination load, or more cooling load.

Having more fenestration can bring more natural light into the building space to reduce the energy consumption for illumination. By locating the windows and shading devices at the correct position, 55.4% percent of regularly occupied floor area of the existing warehouse area can receive ideal daylighting (between 100 and 2000 lux). This can achieve 1 point per the LEED O+M: Existing Buildings V4 standard of daylight Option 1. In addition, the working environment can be improved by having more appropriate daylighting. Workforce motivation can be promoted, and the accident rate can be reduced. However, more solar heat is gathered due to a larger opening, and the interior space temperature is also increased. As a result, the cooling load is increased, although the increased cost is less than the amount saved.

Installing shading devices helps to block unwanted solar heat gain and to reset a new customized cooling schedule that is incorporated with an occupancy sensor and a window operation sensor. The cooling load reduction is significant, as more than 20% of the cooling load (compared to the existing load) can be reduced. Having more access to natural ventilation can increase the air exchange between the interior and exterior space, which provides a better working environment for employees. However, daylighting analysis results show a reduction from the existing situation. Therefore, more interior illumination is required.

It would require much more analysis to weigh the results of each intervention against each other. The challenges of further study will be how to incorporate these two passive strategies to establish the best solution that allows the warehouse to receive sufficient daylighting and a low cooling load at the same time. Daylighting and cooling load work against each other, but are associated closely, which impacts significantly on building performance. Having more fenestration can help to improve daylighting, but then the cooling load is increased. This requires the addition of shading devices to block unwanted solar heat gain, however some of the daylighting is then also blocked. Thus, more illumination will be required. Every design solution always has a tradeoff.

More testing and research is required also to determine the details of shading devices. Different sizes and directions for the devices can affect both passive strategies. Further, this paper does not include any data on the surrounding environment as such information is lacking. The influence of surrounding buildings, surrounding geography, or landscape cannot be ignored to achieve a comprehensive analysis.

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