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Effect of space layouts on the energy performance of office buildings in three climates

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ABSTRACT

Numerous studies have shown that architectural design affects energy performance significantly. However, the effect of space layouts on building energy performance has not been fully analysed. In this paper, we aim to study the effect of space layouts on energy performance. An office building was used as the reference, and 11 layout variants were proposed and compared for energy performance. Three climates (temperate, cold and tropical) were inspected, with three typical cities (Amsterdam, Harbin and Singapore). Dynamic simulation was conducted for the energy performance assessment integrating daylighting simulation with energy simulation. For each layout, two situations were simulated: one has no shading system, and the other one has an exterior screen for shading. Based on the simulation results, it is found that lighting demand is affected the most by the layout variance, and the resulting maximum difference (difference divided by the highest demand) happens in Harbin, being 46% without shading and 35% with shading. Regarding the sum of the final energy for heating, cooling and lighting, using a heat pump system, the maximum difference is 8% for the layouts both without and with shading system occurring in Amsterdam.

1. Introduction

Studies have shown that the architectural design has the highest potential for decreasing the environmental impacts and costs among the whole life-cycle process [1]. Plenty of studies have analysed the impact of geometry factors [2] including orientation, window-to-wall ratio (WWR), and room width-to-depth ratio, envelopes [3], façades, materials [4], and surroundings [5] on the building energy performance (BEP), and their results show that BEP is highly affected. The study of [2] shows that the geometry factors of window orientation, WWR, and room width to depth ratio affect the annual energy consumption in an office building significantly in hot and cold climates, while marginally in temperature climates. The study [3] shows that the properties of envelopes, like thermal mass, airtightness and infiltration, are crucial in influencing building energy consumption. The innovations in solar thermal façade [6], green façade [7], and kinetic façade [8] have been shown to be effective in improving energy performance. The study of [4] shows that the triple-glazing helps to save the cooling consumption by 6.3% compared to a single clear glass. The study of [5] shows that the urban context, considering its influence on casting shadows and reflecting solar radiation, causes a difference from 9% to 12% in the energy consumption between different stories of one building. As an important task of architectural design, space layout design occurs between 'scheme design' and 'design development' in the early design phase [9]. The architectural space layout includes the interior collocation of different rooms, the interior layout, and the placement of interior wall [10]. The geometry of buildings is also affected by space layout design.

The following brief review attempts to isolate the effect of space layouts and refers to the cases in which the effect is attributed solely by space layouts. The effect is indicated as 'maximum difference' (%), which is calculated by dividing the difference between the highest and lowest resulting energy demand by the highest demand. In Ref. [11], five space layouts of an office building in the UK were simulated and their energy demand was compared, and the maximum difference by only changing space layouts was 57% in the heating demand for peak winter and 67% in the lighting demand for peak summer. In Ref. [12], the same five space layouts as in Ref. [11] were simulated and compared for the air volume provided by natural ventilation in peak winter, and the maximum difference was 65%. In Ref. [13], three layouts for an

Abbreviations: BEP, building energy performance; WWR, window-to-wall ratio.

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office building in the UK, which were created with different thermal zoning strategies, were simulated and compared, and the maximum difference was 52% in the heating demand for one year and 24% in the cooling demand. In Ref. [14], two layouts (cell and open) of an office building in Sweden were simulated and compared, and the maximum difference was 14% in the heating demand and 57% in the cooling demand. In Ref. [15], various layouts with the same geometry of a library building in Turkey were simulated and compared, and the maximum difference was 19% in the heating demand per day, 20% in the cooling demand, and 10% for the lighting demand. In Ref. [16], several layouts with the same boundary of an office building in South Korea were simulated and compared, and the maximum difference was 8% in the annual energy use, and 15% in Predicted Mean Vote (PMV). In Ref. [17], various layouts of a residential building in Portugal were simulated and compared, and the maximum difference in the thermal discomfort was 33% for the buildings with one floor and 29% for the buildings with two floors. According to these studies, it is meaningful to fully investigate the effect of space layouts on BEP.

However, most of the relevant studies not only changed space layouts, but also changed other parameters simultaneously. For instance, in addition to space layouts, the studies of [11,12] also changed space use densities, occupancy, and distributions of workstations; the studies of [14–19] also changed WWR. Mixing space layouts with other design parameters makes it impossible to tell the isolated effect of space layouts on BEP. Regarding energy indicators, thermal (heating and cooling) demand was detected in most of the relevant studies, while lighting and ventilation demand was rarely assessed. Some studies only calculated the energy demand for peak days [11,12] or season representative days [15]. Regarding the calculation method of energy performance, although most studies used dynamic simulation, some studies used the simplified steady-state calculation method like in Refs. [18,19]. A systematic study on the effect of space layouts on BEP is needed, in which only space layouts are changed with the other parameters constant, in order to identify the isolated effect of space layouts. In this study an office building was chosen as the reference. The effect of space layouts on the energy demand of heating, cooling and lighting was studied, as well as the effect on the resulting final energy demand.

2. Investigated space layouts and climates

An existing office building is used as the reference, and 11 variants were designed based on the reference space layout. Each layout was simulated in three climates, aiming to measure the different effects of space layouts in different climates.

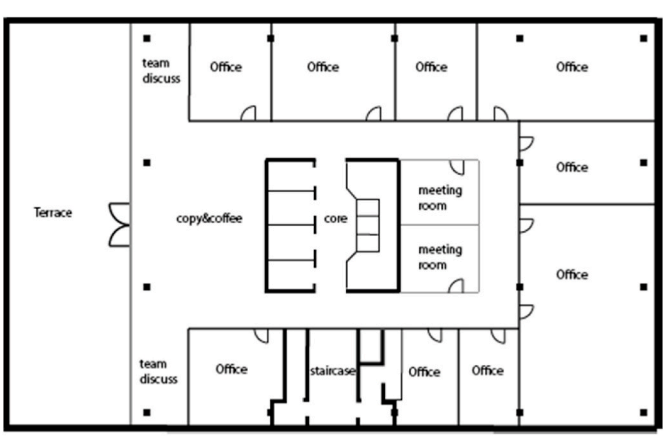


Fig. 1. Space layout of the reference building, adapted from Ref. [20].

2.1. Reference building and investigated space layouts

The space layout of the office building as reference is shown in Fig. 1 [20], and 11 layout variants were designed (Fig. 2) based on the reference layout. These variants were developed according to the layout typologies of office buildings proposed by Yeang [21] with different core locations. Each layout has 12 rooms, and each room is 9 m wide, 9 m deep, and 3 m high (floor to ceiling). The proportion of different functions within a layout affects BEP greatly, as different functions have different requirements for BEP. In this paper, we only studied the variants with the same proportion of different functions: each layout has 6 offices, 2 meeting rooms, 1 canteen, 1 break room, 1 core, and 1 staircase. This proportion is within the threshold of space allocation ratios for office buildings as shown in Ref. [22]. The effect of corridors is ignored and not modelled in these layouts in order to relieve the pressure on simulation. We designed the layout variants that would have the highest or lowest energy demand.

2.2. Investigated climates

Three climates of three typical cities were tested: Amsterdam in the Netherlands for the temperate climate (Appendix-a, b, c), Harbin in China for the cold climate (Appendix-d, e, f), and Singapore for the tropical climate (Appendix-g, h, i). For the calculation of energy demand, we used the method of simulation (see Section 3.4). The study of [23] proposed a new method instead of simulation, to estimate the energy demand in different climates, by using normalisation factors based on air temperature degree days. This method would help to save much computational time compared to simulation. However, this method is not suitable for the goal of this paper, as insulation values and windows types were also adapted according to the common use in the different climates in this study. Besides, the cooling demand was only tested for Central and North European climates in Ref. [23], which is not suitable for this study, in which the tropical climate is also included. Therefore, the simulation method is used in this study to compare the energy demand in different climates. The weather data is from EnergyPlus [24]. The data source of the international weather for energy calculations (IWEC) [25] was used, as it is available for all the three cities.

3. BEP assessment of layouts

The BEP of layouts was assessed with dynamic simulation, coupling daylighting simulation (in Daysim [26], a Radiance [27] based daylighting analysis software) with energy simulation (in EnergyPlus [28]). The reason for coupling Daysim with EnergyPlus is that EnergyPlus has much low accuracy in daylighting simulation. The calculated horizontal illuminances with EnergyPlus has a difference of more than 100% compared to the measured values, as shown in Ref. [29]. Raidance has been proven to be accurate in daylighting simulation for the office with external shading, as shown in Ref. [30]. Coupling EnergyPlus with Daysim helps to improve the accuracy of calculated energy demand by providing a more accurate lighting schedule calculated based on the daylighting simulation. In addition, a detailed daylighting simulation, like multiple lighting zones and multiple dynamic shading groups for one room, is easier to be implemented in Daysim compared to EnergyPlus.

The simulation tools were operated with the plugins of Ladybug and Honeybee for Grasshopper [31] in this study. The effectiveness of the plugins in daylighting and energy simulation has been proved in Refs. [32–34]. The proposed space layouts were simulated for heating, cooling and lighting demand in three climates, and each layout was simulated both with and without a shading system. The detailed method for assessment is shown below.

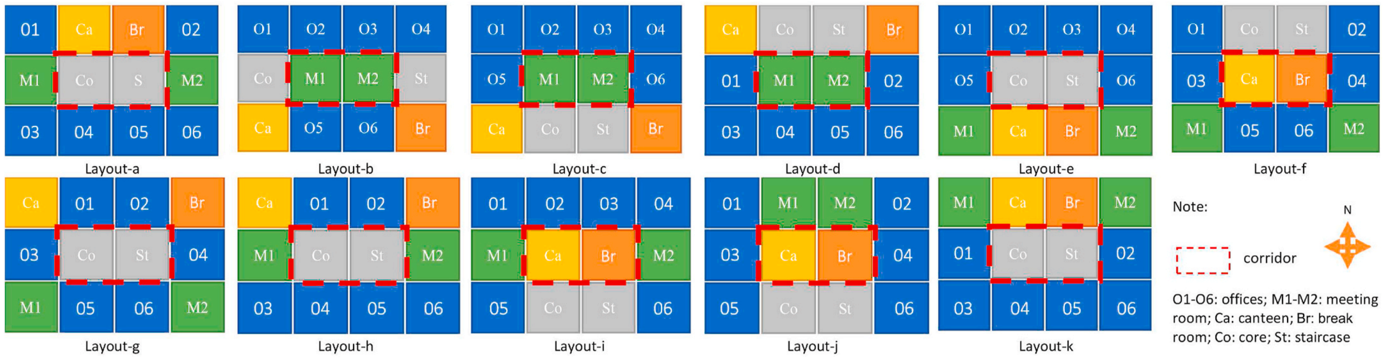


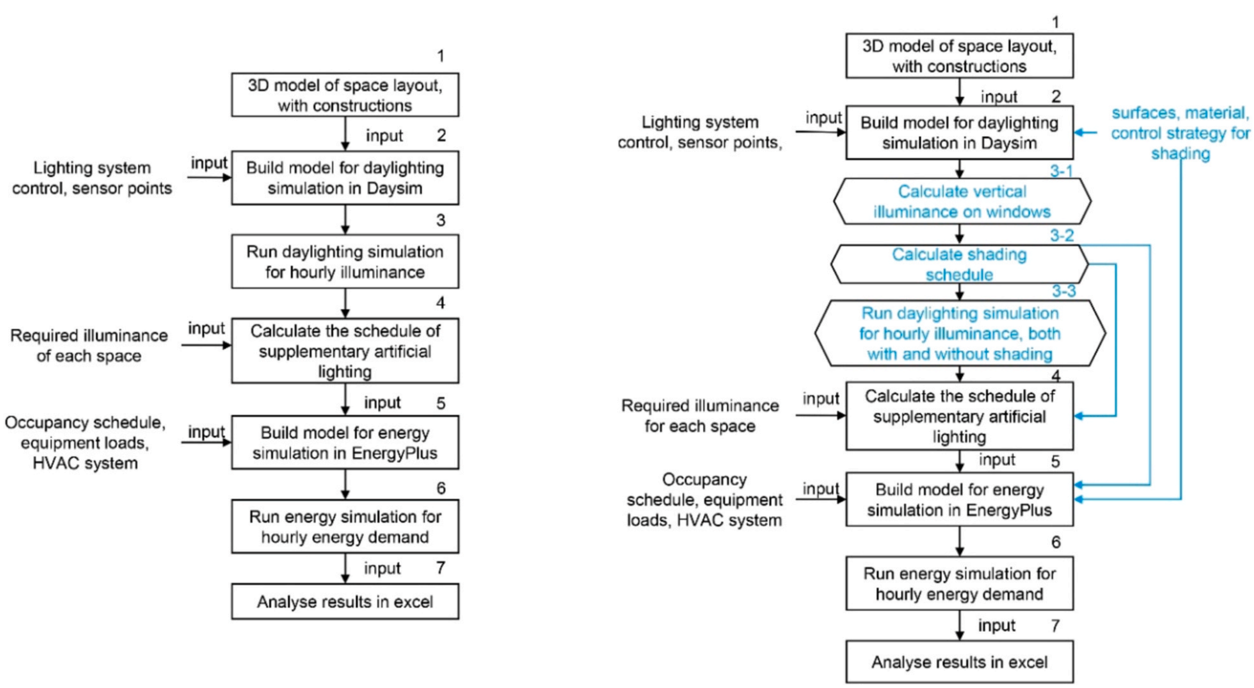
Fig. 2. Proposed 11 variants of the reference layout.

3.1. Procedure for integrating daylighting simulation with energy simulation

A space layout determines the orientation of each room, thereby influencing the amount of daylight penetrating each room. Thus, it influences the lighting demand of the total building. Moreover, the internal gains related to both daylighting and artificial lighting affect the thermal performance of buildings. Hence, only if the influence of daylighting on energy performance is integrated into the simulation process, the calculated results indicate properly the effect of space layouts on BEP. Therefore, daylighting simulation was integrated with energy simulation in the simulation model, and a description of how the simulation tools were integrated is presented below.

For layouts without a shading system, the following procedure was used (Fig. 3-a): step-1, creating the 3D model for the space layout in Grasshopper with constructions; step-2, creating the model for daylighting simulation in Daysim, with the lighting system control and sensor points for each room; step-3, simulating the hourly illuminance of each sensor point for the whole year; step-4, calculating the schedule of the supplementary artificial lighting, based on the calculated daylighting illuminance and the required illuminance of each room; step-5, creating the model for energy simulation in EnergyPlus with occupancy schedule, equipment loads, and HVAC system, as well as the schedule of supplementary artificial lighting; step-6, simulating the hourly energy demand for heating, cooling and lighting in EnergyPlus; step-7, exporting the resulting energy demand to Excel and analysing the results.

For layouts **with** a shading system, the following steps were added to the procedure described above (Fig. 3-b). In step-2, adding the shading system (surface, material and control strategy) to the model for daylighting simulation in Daysim; in step-3, calculating the vertical illuminance on windows in different orientations, and calculating the



a. Procedure of the simulation for the layouts without a shading system

b. Procedure of the simulation for the layouts with a shading system

Fig. 3. Procedure to integrate daylighting simulation with energy simulation.

shading schedule based on the vertical illuminance, and running daylighting simulation twice for each layout (**without** shading and **with** shading); in step 4, calculating the schedule of the supplementary artificial lighting, based on the hourly illuminance both with and without the shading system, as well as the shading schedule obtained from step-3; in step-5, adding the shading system to the model for energy simulation in EnergyPlus, as well as the shading schedule obtained from step-3.

3.2. Simulation model and constructions

The same layouts of the reference building were used for all climates. Regarding the model used for simulation, two models were considered as shown in Fig. 4: in model-a the WWRs of all rooms are the same, i.e. 40%; in model-b, all rooms have the same façade area, so the WWRs of the rooms with one orientation are 40% and the WWRs of all corner rooms are 20%. Comparing the two models, model-a is closer to reality, as corner rooms normally have higher façade areas than the other rooms. Since the aim of this study is test the isolated effect of space layouts on BEP, while keeping the other design parameters constant, both models are suitable. As we think model a is more realistic, model-a with the same WWR in all rooms was chosen for simulation for all three climates.

A WWR of 40% was chosen, in line with the optimal WWR of 30%–45% as recommended for office buildings with shading devices for the climates in Europe covering the latitude of 35°–60° N in Ref. [35], which is suitable for Amsterdam and Harbin. For the tropical climate, the WWR of 25% is recommended for office buildings without shading in Ref. [36], so a higher WWR is expected for office buildings with shading. Therefore, a WWR of 40% is applied for all climates. The distance from the bottom of the window to the floor is 0.8 m. All windows with the height of 2 m are distributed evenly on all facades, and the distance between two adjacent windows is 0.72 m.

The constructions of walls, windows and floors used in the simulation vary between climates, based on local building design standards and customs, as shown in Table 1. The constructions were assigned based on the references of [37–40] for Amsterdam and [41,42] for Singapore. For Harbin, the constructions and materials of glazing and external walls were assigned based on a real project which was constructed in 2018, and the U values were assigned based on [43].

3.3. Daylighting simulation and artificial lighting system

The daylight simulation was used to determine the amount of the supplementary artificial lighting needed to reach the required illuminance. In this study, the daylight-linked dimming was used to control the lighting system: the lamp is only switched on when the room is

Table 1
Details of walls, floors and glazing used for the layouts in three climates.

Construction of wall and floor			
Name	**Layers (from inside to outside)**		**U value (W/m^2K)**
Interior wall for all climates	19 mm Gypsum board + air space resistance+19 mm Gypsum board;		2.56
Interior floor for all climates	Acoustic tile + ceiling air space resistance + 100 mm lightweight concrete;		1.45
Exterior wall for Amsterdam [37]	100 mm brick + 25 mm air cavity + 140 mm insulation + 150 mm concrete;		0.22
Exterior wall for Singapore [41]	25 mm plaster + 300 mm concrete + 50 mm insulation + 12 mm plasterboard + 12 mm plaster;		0.5
Exterior wall for Harbin	20 mm cement mortar + 150 mm rigid polyurethane foam + 20 mm cement mortar + 200 mm concrete + 20 mm lime mortar;		0.18 [43]
Glazing properties			
Location	**U value (W/m^2K)**	**Visible transmittance**	**g value**
Amsterdam	1.65 [38]	0.76 [40]	0.7 [39]
Singapore	1.6 [42]	0.59 [41]	0.27 [41]
Harbin	2.2 [43]	0.8	0.54
Reflectance of interior surfaces			
Floor	**Ceiling**	**Wall**	
0.1	0.8	0.5	

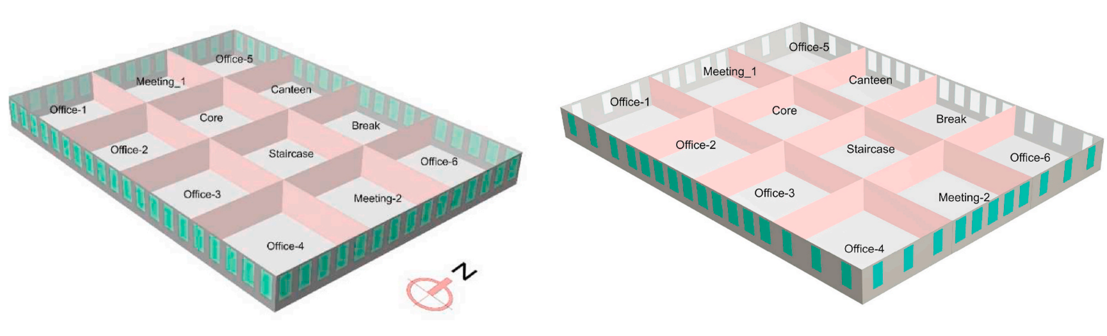
occupied and is dimmed to output the illuminance based on the available daylighting illuminance until the work plane receives the required illuminance. The modelling details are shown below.

3.3.1. Test points and simulation parameters for daylighting simulation

The test points for daylighting simulation are distributed evenly in 12 rooms within the layout. These test points are located on a grid resolution of 1 m × 1 m, and the vertical distance from the test point to the base surface is 0.8 m. The reflectance of the interior surfaces is shown in Table 1. The Radiance simulation parameters are as follows [44]: ab (ambient bounces) is 5; ad (ambient divisions) is 1024; as (ambient super samples) is 16; ar (ambient resolution) is 256; aa (ambient accuracy) is 0.1.

3.3.2. Target illuminance and properties of the artificial lighting system

As recommended in Ref. [45], different functions need different illuminance levels, and the illuminance levels used in this study are as



Model-a: with 40% WWR for all rooms

Model-b: 40% WWR for the rooms with one orientation and 20% WWR for corners

Fig. 4. Simulation models for one layout.

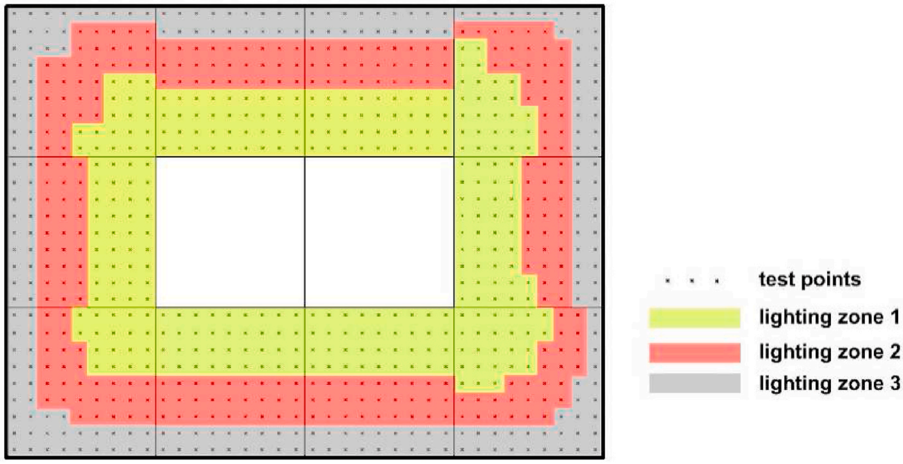


Fig. 5. Test points and lighting zones for lighting system control (the two middle rooms do not have daylighting).

Table 2
Control strategy for the shading system.

Period	Working period (9:00–17:00)			Off-working period (0:00–8:00, and 18:00–23:00)
	Occupied		Non-occupied	
	Glare	No glare		
Non-cooling period	On (to avoid glare)	Off (for more daylight)	Off (for more solar gains)	Off (to increase solar gains in early morning and late afternoon)
Cooling period	On (to avoid glare)	Off (for more daylight)	On (to reduce solar gains)	On (to reduce solar gains in early morning and late afternoon)

Note: the thermal property of the screen is not considered in this study.

follows: 500 lux for offices, 300 lux for meeting rooms, 200 lux for break rooms and canteens, and 150 lux for staircases and cores. An energy-efficient lamp was used for lighting with the luminaire efficacy of 138 lm/W and initial luminous flux of 4000 lm, which is in accordance with the Philips SM530C L1130 1 × LED40S/840 OC [46]. The room index is 2, and it is used to determine the utilisation factor of each room. Calculated based on the photometric data of the lamp and the reflectance of ceilings, walls and floors, the utilisation factor is 0.97. The maximum lighting power density, which is needed for the required illuminance of each room, was calculated based on the 'lumen method' [47]. The density for each room is as follows: 4.7 W/m^2 for offices, 2.8 W/m^2 for meeting rooms, 1.9 W/m^2 for break rooms and canteens, 1.4 W/m^2 for staircases and cores. The other properties of the lighting system are as follows: the standby power is 1% of the lamp power (29 W), i.e. 2.9 W; the delay time of sensors is 5 min; the ballast loss factor is 0%, as LED luminaires do not use ballast.

3.3.3. Control of lighting system

As for the control of lighting system, each room was divided into three lighting zones, as shown in Fig. 5, using the following procedure: (1) the hourly daylight illuminance (without shading) of each test point is summed up for one year; (2) the natural logarithm of the annual value is calculated for each test point; (3) the values of all test points are divided into three domains; (4) all test points within one room are classified into three groups based on the three domains; the corresponding area of each group is one lighting zone. Since the middle rooms do not receive any daylight, no test point is assigned to them. Within one lighting zone, the artificial lighting system was adjusted to meet the target illuminance based on the daylight illuminance of the test point that has the lowest annual daylighting illuminance. The supplementary artificial lighting schedule of each room was calculated as follows: (1) the ratio between the required illuminance, i.e. the difference between the target illuminance and the received daylighting illuminance, and the target illuminance is calculated for each lighting zone; (2) the illuminance ratio is multiplied by the corresponding area ratio of the lighting zone; (3) the values of three lighting zones are summed up for each room. For the energy simulation, the artificial lighting power calculated for three lighting zones in each room is used as the internal gains for the room.

3.3.4. Shading system

The daylighting performance was investigated both with and without a shading system. In this study, an exterior screen is assumed for each window and is automatically controlled based on the possibility of glare. In corner rooms, shading screens were installed on two facades, and they were controlled separately based on the vertical illuminance on each facade.

- Shading material and control strategy

The exterior screen of Dickson sun worker open M005 was selected from Ref. [48] and used in this study. Its properties are as follows: the thickness is 0.00055 m; the emissivity is 0.77; its g-value is 0.32; the visible transmittance is 0.31; the diffuse visible transmittance is 0.14; the visible reflectance is 0.60; the heat resistance is 0.0069; the conductivity is 0.08 W/m·K. The control strategy for shading used in this study is shown in Table 2. During the non-cooling period, when a room was occupied and there was glare, the screen was turned on for shading; at the other time the screen was turned off to have more solar gains. During the cooling period, when a room was occupied and had no glare, the screen was turned off for more daylight; at the other time the screen was turned on to have less solar gains.

- Calculation of the vertical illuminance on windows for shading control

In this study, the shading system was controlled based on the possibility of glare. There are various indicators for glare, varying from the simply one of the illuminance on windows [49] to the specific ones, like BRS glare equation, daylight glare index (DGI), CIE glare index (CGI), CIE's unified glare rating system (UGR), and daylight glare probability (DGP), as shown in Ref. [50]. However, the specific indicators are sensitive to furniture layouts, view directions of occupants, window frames, etc., which differ between different rooms and cannot be specified in this study. So we used the vertical illuminance on windows as the indicator for glare possibility. The set-point for shading is 15,000 lux of the vertical illuminance on windows, as recommended in Ref. [49].

3.4. Energy simulation

The heating and cooling demand were calculated in EnergyPlus with the ideal loads air system [51]. The details for energy simulation are shown below.

- Ventilation and infiltration

The outdoor air flow rate is 0.37 $dm^3/s{\cdot}m^2$ (per floor area) plus 8.89 $dm^3/s{\cdot}$person, as recommended in Ref. [39]. For all climates, a heat exchanger was used with a heat recovery efficiency of 0.7. The humidity threshold is 25%–60%, as recommended in Ref. [52]. The infiltration rate is 0.2 air changes per hour and the middle rooms have no infiltration.

- Temperature set-points for heating and cooling

Different functions have different requirements for the thermal comfort temperature. The temperature set-points for cooling and heating are as follows: 24°C (cooling) and 22°C (heating) for offices and meeting rooms, 26°C (cooling) and 20°C (heating) for canteens and break rooms, 28°C (cooling) and 18°C (heating) for staircases and cores. The set-back points for cooling and heating are the same for all rooms, being 30°C and 15°C respectively. The temperature set-points were assigned based on NEN 16798–1 [52].

- Internal gains of occupants and equipment

The applied maximum occupancy and equipment load density for each function are shown in Table 3. The applied maximum equipment load densities are the values defined in Honeybee for office buildings, which were assigned based on the data collected by the U.S. Department of Energy for Commercial Reference Buildings [53].

- Schedule

The occupancy schedule is shown in Fig. 6. The occupancy schedule differs between functions, as different activities happen at different periods. The average occupancy schedule (the maximum occupancy multiplied with the schedule fraction) of offices for one day is around 0.3, which is in accordance with the Dutch standard NTA 8800 [54]. For the comparability of the results, the same schedules were assumed for the three climates. The maximum occupancy and occupancy schedule were designed in order to get close to the real situation and to show the difference between functions.

Table 3
Maximum internal gains of different spaces.

Spaces	Max. occupancy (persons/room)	Max. equipment load density (W/m^2)
Office	6	6.9
Meeting room	12	4
Canteen	9	48
Break room	9	0.8
Staircase	3	0
Core	3	3

4. Results and analysis

In order to compare the results between layouts, the maximum difference (%), as explained in Section 1, was used as the indicator to show the effect of space layouts on BEP. In this section, energy demand was compared, as well as the resulting final energy demand. The **energy demand** (or energy need) for heating or cooling refers to the 'heat to be delivered to or extracted from a conditioned space to maintain the intended temperature conditions during a given period of time' [55]. The **final energy** for heating or cooling refers to the energy input to the heating or cooling system to satisfy heating and cooling respectively [55], which is in the form of the energy carrier bought at the meter, such as electricity. Comparing final energy helps to identify the effect of space layouts on the overall energy use of buildings, as the efficiency of transferring the delivered energy for demand varies between heating, cooling and lighting. Energy demand was obtained from the simulation of EnergyPlus, and final energy was calculated based on some assumptions concerning energy supply system.

4.1. Comparison of energy demand

The resulting heating, cooling and lighting demand of all layouts in the three climates are presented in Table 4, and they are compared below.

4.1.1. Overall results of energy demand

Among all maximum differences in energy demand for all cases in Table 4, the **lighting demand** has the greatest maximum difference; the maximum differences in heating and cooling demands are significantly lower. The maximum differences in lighting demand is the highest, and the highest values occur in Harbin, being 46% without shading and 35% with shading. The values without shading are higher than the values with shading, and this is because the difference in received daylight is reduced as a result of shading. The maximum difference in **heating demand** is relatively low, and the highest difference occurs in Amsterdam, being 11% and 18% for without shading and with shading respectively. Apparently, the additional internal gains from artificial lighting have a higher influence on the fluctuation of heating demand with the reduction of solar gains. The highest value of the maximum difference in **cooling demand** occurs in Amsterdam, being 8% for without shading and 11% for with shading.

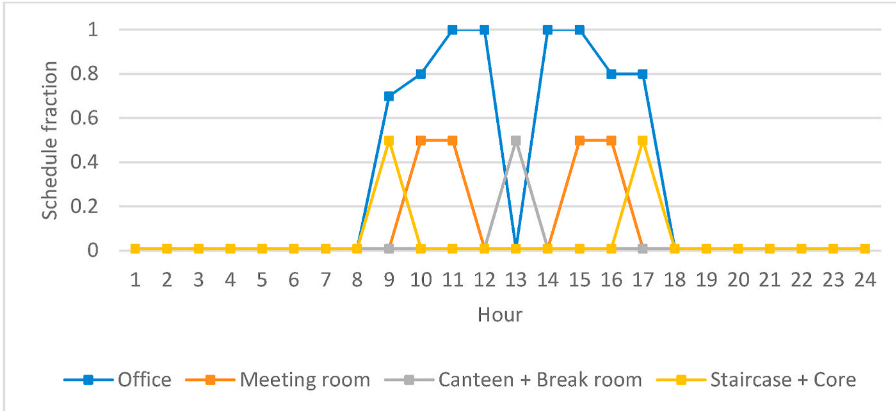


Fig. 6. Occupancy schedule for different functions.

Table 4
Energy demand of all layouts in the three climates.

	Energy demand of Amsterdam (kWh/m²)						Energy demand of Harbin (kWh/m²)						Energy demand of Singapore (kWh/m²)			
	Without shading			With shading			Without shading			With shading			Without shading		With shading	
	H	C	L	H	C	L	H	C	L	H	C	L	C	L	C	L
Layout-a	14.2	12.1	1.8	17.3	4.3	2.2	37.8	36.6	1.3	41.4	16.8	1.7	229	1.5	132	2.1
Layout-b	12.8	11.4	2.7	14.9	4.1	2.9	36.9	36.2	2.2	38.6	16.1	2.5	232	2.2	137	2.8
Layout-c	12.8	11.3	2.8	14.5	4.0	3.0	36.8	36.3	2.4	37.9	16.4	2.6	227	2.2	137	2.7
Layout-d	13.0	11.9	2.4	15.8	4.5	2.8	37.0	36.4	1.9	40.1	16.3	2.3	234	2.2	137	2.7
Layout-e	13.8	12.0	2.4	16.1	4.2	2.6	37.5	37.2	2.0	39.4	17.1	2.2	228	1.8	135	2.4
Layout-f	13.6	12.2	2.2	16.3	4.4	2.5	37.4	37.0	1.6	40.3	17.0	2.0	230	1.8	134	2.4
Layout-g	13.5	12.1	2.7	16.0	4.3	3.0	37.3	36.8	2.2	39.7	16.5	2.5	230	2.3	137	2.9
Layout-h	13.8	12.0	2.3	16.6	4.3	2.7	37.5	36.6	1.8	40.6	16.4	2.2	230	2.0	135	2.6
Layout-i	13.7	11.6	2.1	16.2	4.0	2.3	37.5	36.5	1.6	39.8	16.7	1.8	225	1.5	132	2.1
Layout-j	13.8	11.7	2.0	16.4	4.1	2.3	37.7	36.7	1.5	40.2	16.8	1.8	224	1.4	132	2.0
Layout-k	14.3	12.3	2.1	17.6	4.4	2.5	37.8	36.8	1.5	41.4	16.8	2.0	230	1.8	134	2.4
Absolute maximum difference	1.5	1	1	3.1	0.5	0.8	1	1	1.1	3.5	1	0.9	10	0.9	5	0.9
Maximum difference (%)	**11%**	**8%**	**35%**	**18%**	**11%**	**27%**	**3%**	**3%**	**46%**	**9%**	**6%**	**35%**	**4%**	**37%**	**4%**	**31%**

Note: The blue value represents the lowest value of a given column, and the red value represents the highest. H: heating; C: cooling; L: lighting. Absolute maximum difference refers to the biggest difference between the best layout and worst layout (kWh/m2)

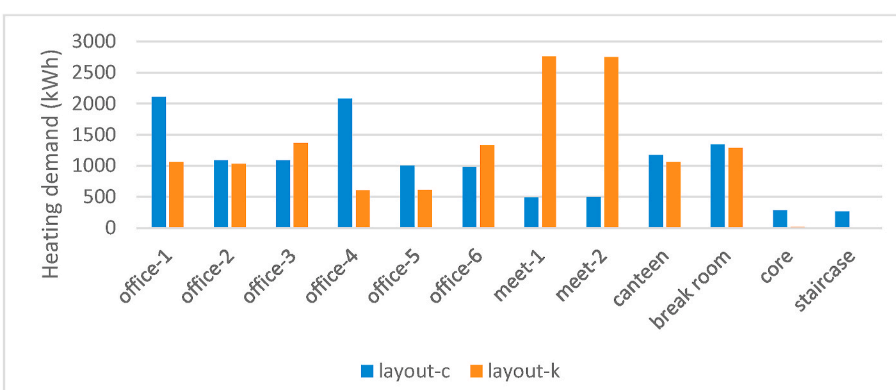


Fig. 7. Heating demand of layout-c and layout-k without the shading system for Amsterdam.

4.1.2. Detailed discussion of the results for Amsterdam

This subsection presents the detailed analysis of the results for Amsterdam. The heating, cooling and lighting demand of the layouts without and with shading are shown in Table 4 and compared below.

- Lighting demand for Amsterdam

Compared to the results without shading, lighting demand of all layouts with shading increases strongly. The maximum difference between the layouts with shading is smaller than between the layouts without shading (27% versus 35%). For both with and without shading, layout-c has the highest lighting demand among all layouts. In layout-c, two offices which have the highest illuminance requirement are oriented

North, and the meeting rooms which have the second highest illuminance requirement are located in the middle, where no daylight is available. For both with and without shading, layout-a has the lowest lighting demand among all layouts. In layout-a, offices are located in South and corners, where receive the most amount of daylight.

- Heating demand for Amsterdam

Among all layouts both without and with shading, layout-k has the highest heating demand and layout-c has the lowest. The maximum difference in heating demand is 11% without shading and 18% with shading. Generally, the room with a high temperature set-point for heating, office in this study, should be located in South to receive more solar gains, so that one would expect that layout-k would have the lowest heating demand. However, layout-k results in the highest heating demand and layout-c, in which two offices are located in North, results in the lowest heating demand. With further analysis, the reasons for the difference between layout-c and layout-k are found as follows:

a. According to the comparison of heating demand between layout-c and layout-k (Fig. 7), the difference between the two layouts is mainly caused by the difference occurring in meeting rooms. In layout-c, meeting rooms are located in the middle, where there is not heat loss to the outside, while in layout-k, they are located in the NW and NE corners.
b. The lighting demand, and therefore internal lighting gains, of layout-c is higher than layout-k (see Table 4), so the difference in heating demand is partly caused by the artificial lighting gains.

- Cooling demand for Amsterdam

Among all layouts with shading, layout-k has the highest cooling demand and layout-c has the lowest, which is the same as heating demand. The maximum difference in cooling demand is 11%, which is even smaller than heating demand. In summer, solar gains are much higher than lighting gains in Amsterdam. The function with the highest cooling requirement, office in this study, should be located in North, where has less solar gains, and the function with the lowest cooling requirement, core and staircase in this study, should be located in South, which is the case for layout-c. For the cases without shading, the maximum difference in cooling demand is 8%, which is relatively small.

4.1.3. Detailed discussion of the results for Harbin

The simulation results of Harbin are shown in Table 4 and compared below. The maximum difference in heating demand is 3% without shading and 9% with shading. The maximum difference in cooling demand is 3% without shading and 6% with shading. They are much smaller than the difference in lighting demand, and therefore are not further discussed. Among all layouts, the maximum difference in lighting demand is 46% without shading and 35% with shading. Layout-a has the lowest lighting demand for both without and with shading, which is caused by the offices located in South and corners. Layout-c has the highest lighting demand for both without and with shading. It is because in layout-c two offices are located on the North side and meeting rooms are located in the middle.

4.1.4. Detailed discussion of the results for Singapore

The simulation results of Singapore are shown in Table 4. The maximum difference in cooling demand is 4% without shading and 4% with shading, which is negligible. Therefore, only lighting demand is compared. Among all layouts both without and with shading, layout-g has the highest lighting demand and layout-j has the lowest, and the maximum difference is 37% for without shading and 31% for with shading. In Singapore, the East and West receive more solar radiation than the North and South, as shown in Appendix-i. In layout-j, all offices are located on the East and West side, while in layout-g, most offices are located on the North and South.

4.2. Comparison of the final energy

In order to compare the overall energy performance, the energy demand cannot be simply summed up, as they are not in the same type of energy carrier. In order to assess the overall energy performance, energy demand must be converted to final energy, as explained at the beginning of Section 4. For all layouts, an air-source heat pump was assumed to be used for heating and cooling. The theoretically ideal COP (COP_{carnot}) [56] was calculated monthly for each climate, based on the supply temperature (35 C for floor heating and 5 C for cooling with chilled water [57]) and the monthly minimum (for heating) and maximum (for cooling) average outdoor temperature. The real COP (COP_{real}) is between 40% and 60% of COP_{carnot} as shown in Ref. [56]. So, the COP_{carnot} was multiplied with 50% to obtain the COP_{real} in this study. With the COP_{real}, the final energy for heating and cooling was calculated. For lighting, the artificial lighting demand is already in form of electricity and thereby the final energy for lighting is the same as lighting demand. The sum of the calculated final energy for heating, cooling and lighting for the three climates is shown in Table 5. The highest maximum difference in the sum of final energy is 8% for layouts without shading which happens in Amsterdam, and 8% for layouts with shading which also happens in Amsterdam.

4.3. Discussion

To better understand the reasons for the differences between layouts, we analysed the energy demand of each function in different locations, based on the results obtained from the energy simulation.

Table 5
The sum of the final energy for heating, cooling and lighting for the three climates.

	Final energy for different layouts (kWh/m^2)											Maximum difference (%)
	a	b	c	d	e	f	g	h	i	j	k	
Sum of the final energy of Amsterdam												
With shading	7.7	7.8	7.7	7.9	7.8	7.8	8.1	8.0	7.5	7.5	8.1	**8%**
Without shading	7.9	8.3	8.4	8.1	8.4	8.1	8.6	8.3	8.0	7.9	8.2	**8%**
Sum of the final energy of Singapore												
With shading	36.1	38.1	37.9	37.9	37.1	36.9	38.3	37.4	36.1	36.1	36.8	**6%**
Without shading	60.4	61.9	60.5	62.3	60.6	61.0	61.6	61.2	59.2	59.2	60.9	**5%**
Sum of the final energy of Harbin												
With shading	21.8	21.3	21.2	21.8	21.6	21.8	21.9	21.9	21.3	21.4	22.1	**4%**
Without shading	24.1	24.6	24.8	24.4	24.9	24.4	24.8	24.5	24.3	24.3	24.5	**3%**

Note: The blue value represents the lowest value of a given row, and the red value represents the highest.

Lighting demand without shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		463	396	336	403	175	180	246	220	288
meeting	236	106	82		85	26	27	38	32	210
break	40	12		5				2		38
canteen	40	11		4					1	39
core	59	25		21	22					38
staircase	59	26	24	21						38

lighting demand with shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		473	439	428	458	234	223	271	246	250
meeting	236	106	94		99	34	32	42	33	203
break	40	12		8				2		38
canteen	40	11		6					2	38
core	59	28		25	27					34
staircase	59	29	25	26						34

best location: corners; worst location: M

Heating demand without shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		1185	1017	585	1038	1398	1366	2174	2205	1620
meeting	528	1671	1462		1481	1734	1705	2748	2759	2231
break	243	1287		585				2146		1904
canteen	158	1061		485					1867	1709
core	15	770		287	505					755
staircase	12	752	465	275						740

Heating demand with shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		1367	1229	779	1246	1756	1693	2525	2592	1814
meeting	643	1978	1798		1815	2081	2011	3276	3310	2667
break	303	1529		666				2426		2123
canteen	197	1249		544					2133	1936
core	26	900		305	587					875
staircase	21	879	524	292						857

best location: M,S; worst location: corners

Cooling demand without shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		842	1362	1484	1375	1926	1883	1256	1278	1085
meeting	531	498	998		1015	1599	1552	961	992	1100
break	130	159		612				494		483
canteen	297	313		829					670	532
core	12	41		377	306					366
staircase	12	40	276	372						360

Cooling demand with shading, Amsterdam (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		398	511	592	547	695	672	494	497	297
meeting	201	167	256		284	458	437	267	268	290
break	14	63		73				136		122
canteen	80	83		162					153	82
core	6	63		26	29					57
staircase	6	66	38	27						60

best location: M,N; worst location: corners

Lighting demand without shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		408	337	235	328	86	105	166	150	322
meeting	236	86	62		56	7	11	18	15	229
break	40	8		0				0		40
canteen	40	8		0					0	40
core	59	18		14	14					45
staircase	59	18	15	14						45

Lighting demand with shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		421	377	342	400	143	153	188	180	278
meeting	236	87	78		74	13	17	23	17	223
break	40	8		3				0		40
canteen	40	8		3					0	40
core	59	22		16	19					43
staircase	59	22	15	16						44

best locations: corners; worst locations: M

Heating demand without shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		3704	3087	1854	3124	3914	3840	6310	6330	4476
meeting	1020	3730	3067		3114	3753	3680	6355	6372	5351
break	429	3183		1190				5611		5182
canteen	373	2893		1218					5326	4953
core	134	2681		953	1911					2548
staircase	121	2663	1866	946						2541

Heating demand with shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		3970	3275	2058	3449	4305	4038	6610	6907	4849
meeting	1144	4069	3354		3501	3928	3683	6749	6981	5836
break	512	3526		1134				5766		5254
canteen	417	3193		1099					5680	5262
core	178	2976		846	2032					2798
staircase	160	2936	1884	837						2776

best locations: M,S; worst locations: corners, N

Cooling demand without shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		2598	4165	3631	3834	5141	5370	4411	4132	2772
meeting	1456	1792	3332		3049	4406	4620	3660	3453	3164
break	681	1042		2096				2796		2116
canteen	1134	1677		2759					2975	1841
core	134	549		1485	1547					1413
staircase	161	605	1835	1516						1674

Cooling demand with shading, Harbin (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		1651	2120	1998	2113	2507	2497	2166	2138	856
meeting	885	882	1277		1258	1687	1690	1317	1286	809
break	143	167		418				431		288
canteen	442	417		810					672	392
core	18	68		103	79					85
staircase	17	66	97	112						95

best locations: M,N; worst locations: corners

Lighting demand without shading, Singapore (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		365	316	350	349	132	124	110	119	255
meeting	236	77	56		67	12	14	9	10	227
break	40	8		7				0		40
canteen	40	8		5					0	40
core	59	12		9	10					50
staircase	59	12	8	10						51

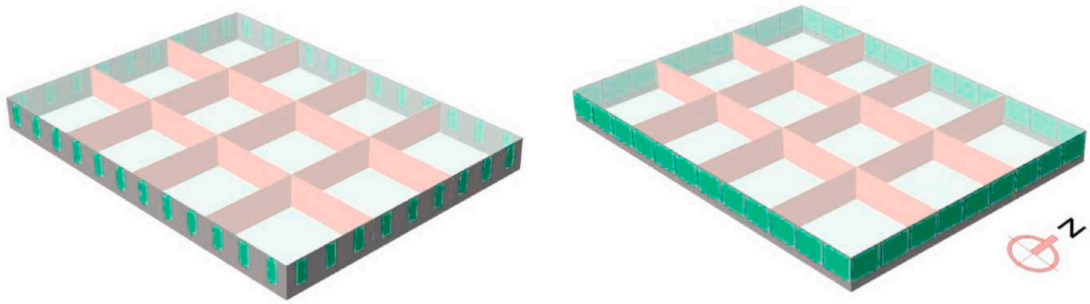
Lighting demand with shading, Singapore (kWh)

	M	N	E	S	W	C_sw	C_se	C_ne	C_nw	difference
Office		463	397	445	439	206	189	197	203	274
meeting	236	107	81		89	30	23	31	26	213
break	40	14		12				4		36
canteen	40	14		12					3	37
core	59	19		16	18					43
staircase	59	18	10	16						49

best location: corners; worst lcoation: M,N

Note:
The gradient colour represents the value relative to the other values. As for the energy demand of each space, green means lowest, red means highest. Here, the difference refers to the 'greatest difference'. As for the greatest demand, the darker the colour is, the greater the difference is. Here, the greatest difference refers to the difference in the energy demand of each function between the worst location and best location in the layout.
N: north; E: east; S: south; W: west; M: middle; C_sw, C_se, C_nw, C_ne: different corners.

Fig. 8. Energy demand of each function in different locations.



a. The example model with WWR of 20%

b. The example model with WWR of 60%

Fig. 9. Simulation models with WWR of 20% and 40%.

Table 6
Maximal and minimal energy demand and the maximum difference (%) among 11 layouts with the WWR of 20% and 60% in three climates.

	Energy demand of Amsterdam (kWh/m^2)						Energy demand of Harbin (kWh/m^2)						Energy demand of Singapore (kWh/m^2)			
	Without shading			With shading			Without shading			With shading			Without shading		With shading	
	H	C	L	H	C	L	H	C	L	H	C	L	C	L	C	L
WWR 20%																
Max	11.3	7.3	3.8	13.2	3.7	3.9	31.8	23.5	3.5	34.3	14.6	3.9	144.8	3.4	111.1	4.0
Min	9.8	6.8	3.0	10.8	3.3	3.4	30.6	22.9	2.4	31.6	13.7	2.9	141.0	2.6	108.9	3.3
Absolute maximum difference	1.5	0.6	0.8	2.4	0.4	0.5	1.2	0.6	1.1	2.7	0.9	1.0	3.8	0.9	2.2	0.6
Maximum difference (%)	**13%**	**8%**	**21%**	**18%**	**12%**	**13%**	**4%**	**2%**	**33%**	**8%**	**6%**	**25%**	**3%**	**25%**	**2%**	**16%**
WWR 60%																
Max	17.6	16.6	2.2	21.4	5.5	2.4	45.4	49.7	2.0	48.4	21.8	2.3	325.4	1.6	172.3	2.2
Min	16.1	15.1	1.3	18.1	4.9	1.6	44.3	48.3	0.7	44.9	19.0	1.1	311.6	0.7	165.0	1.4
Absolute maximum difference	1.5	1.5	0.9	3.4	0.7	0.8	1.1	1.4	1.2	3.5	2.8	1.3	13.8	0.9	7.3	0.8
Maximum difference (%)	**8%**	**9%**	**42%**	**16%**	**12%**	**33%**	**2%**	**3%**	**63%**	**7%**	**13%**	**55%**	**4%**	**55%**	**4%**	**38%**

Note: H: heating; C: cooling; L: lighting. Max: the maximal energy demand among 11 layouts, kWh/m2; Min: the minimal value among 11 layouts, kWh/m2. Absolute maximum difference refers to the biggest difference between the best layout and worst layout (kWh/m2).

Table 7
U values of exterior wall and glazing for poor insulated buildings in the three climates.

	U value (W/m^{2}K)
Exterior wall, Amsterdam	0.4
Exterior wall, Singapore	1.0
Exterior wall, Harbin	0.36
Glazing, Amsterdam	3.3
Glazing, Singapore	3.2
Glazing, Harbin	4.4

In Fig. 8, the energy demand of each function in each location is presented and the gradient colour represents the value relative to the other values. As shown in the last column of each situation, the **greatest difference** refers to the difference in the energy demand of each function between the worst location and best location of the layout. For example, the greatest difference of offices in lighting demand without shading of Amsterdam is the difference between North (highest) and SE corner (lowest). As shown in Fig. 8, the same locations can be the best or worst for energy demand among all locations. So the function that benefits the most from the best location should be placed there.

As for the **heating demand** for Amsterdam and Harbin, the greatest differences of meeting rooms, break rooms and canteens are much higher than offices. As for the **cooling demand** for Amsterdam and Harbin, the greatest differences of meeting rooms and offices are much higher than other functions. As for the **best and worst locations** of layouts, corners are always the best for lighting and worst for heating and cooling, and in contrast, the middle is always the best for heating and cooling and worst for lighting (except for offices which cannot be located in the middle). Hence, the layout with the lowest energy demand is the one that allocates the functions, following the order of the greatest differences from high to low, to the locations from best to worst sequentially. The order of the greatest difference should be updated if one location is occupied.

In conclusion, there is a **trade-off** between the highest difference in lighting, heating, and cooling demand for each function in different locations, as well as a trade-off between the best and worst locations in layouts for lighting, heating and cooling demand. The layout with the lowest energy demand is the result of an optimisation process that can be seen as a 'battle for the best location', won by the function that benefits the most from a certain location. It is these trade-offs that make the prediction of the most energy-efficient layout difficult.

5. Sensitivity analysis of design parameters

In order to better understand the influence of space layouts on BEP in combination with other building properties, two design parameters were tested for their influence on the maximum difference in each energy demand between layouts of three climates in this section, i.e. WWR and U value.

5.1. Sensitivity analysis for different WWRs

In addition to the WWR of 40% in the previous model shown in Section 3, two additional WWRs were tested, i.e. 20% and 60%, as shown in Fig. 9.

The two WWRs were tested for the 11 layouts in the three climates, and the resulting maximum and minimal energy demand and the maximum difference between 11 layouts are shown in Table 6.

Comparing the results from the simulations with a WWR of 20% and 60% in Table 6 with the results using a WWR of 40% in Table 4, the

Table 8
Maximal and minimal energy demand and the maximum difference (%) among 11 layouts with U values for poor insulated buildings with the WWR of 40% in three climates.

	Energy demand of Amsterdam (kWh/m^2)						Energy demand of Harbin (kWh/m^2)						Energy demand of Singapore (kWh/m^2)			
	Without shading			With shading			Without shading			With shading			Without shading		With shading	
	H	C	L	H	C	L	H	C	L	H	C	L	C	L	C	L
Max	16.1	11.9	2.8	19.6	4.4	3.0	40.8	36.9	2.5	44.4	17.8	2.8	236.5	2.2	140.0	2.9
Min	14.5	10.9	1.8	16.3	3.9	2.3	39.7	35.8	1.2	40.5	15.9	1.7	227.1	1.4	134.6	2.0
Absolute maximum difference	1.5	1.5	0.9	3.4	0.7	0.8	1.1	1.4	1.2	3.5	2.8	1.3	13.8	0.9	7.3	0.8
Maximum difference (%)	**10%**	**8%**	**34%**	**17%**	**12%**	**25%**	**3%**	**3%**	**51%**	**9%**	**11%**	**42%**	**4%**	**38%**	**4%**	**30%**

Note: H: heating; C: cooling; L: lighting. Max: the maximal energy demand among 11 layouts, kWh/m2; Min: the minimal value among 11 layouts, kWh/m2. Absolute maximum difference refers to the biggest difference between the best layout and worst layout (kWh/m2).

following results were found. The maximum difference in thermal energy between layouts hardly changes or changes slightly (in Amsterdam without shading) with the change of WWRs, while the maximum difference in lighting demand between layouts increases highly with the increase of WWRs, for both with shading and without shading. This is because although the absolute maximum differences (kWh/m^2) in heating and cooling demand vary between different WWRs, like 2.4 kWh/m^2 for 20% WWR and 3.4 kWh/m^2 for 60% WWR in Amsterdam with shading, the value of heating and cooling demand for each layout is much higher than the value of absolute maximum difference, like 21.4 kWh/m^2 for WWR 60% in Amsterdam with shading. Thus, the relative variation in the maximum difference (%) of heating and cooling demand is little. However, the lighting demand is the opposite. The absolute maximum difference matters relatively more compared to the total lighting demand of each layout. For example, the absolute maximum difference in lighting demand is 0.9 kWh/m^2 while the total lighting demand of the layout with the lowest demand is only 1.3 kWh/m^2.

5.2. Sensitivity analysis for different U values

The U values used in the previous model as shown in Table 1 were chosen based on local regulations and they result in good insulation of the building. The building with poor insulation was tested in this Section to simulate existing buildings which need to be renovated for energy performance improvement, with double U values of external walls and glazing used in the previous model, as shown in Table 7.

The U values for poor insulated buildings were tested for the 11 layouts in the three climates, and the resulting maximal and minimal energy demand and the maximum difference between 11 layouts are shown in Table 8.

Comparing the results from the simulations with the U values for poor insulated buildings in Table 8 with the results for good insulated buildings in Table 4, it is found that with the change of U values, the maximum differences (%) in heating, cooling and lighting demand are hardly changed in the three climates, for both with shading and without shading. Thus, U values of exterior wall and glazing have little influence on the effect of space layouts on BEP.

5.3. Overall conclusion on the sensitivity analysis

This sensitivity analysis has shown that the impact of space layout can be affected by other building properties as well. It was shown that the WWR has a significant impact on the effect of space layouts on lighting demand, but only a minor impact on thermal demand. The impact of U-value on both heating, cooling and lighting, is relatively small, regarding the model used in this study. For case studies with a different (e.g. less compact) geometry, this effect could be different. In general, it indicates that the higher the difference in properties between different locations in a building, the higher the impact of changing the space layout on BEP.

6. Conclusions, recommendations and limitations

In this paper, the energy demand of 11 space layouts for an office building were simulated and compared, and their final energy was calculated and compared in three climates with three typical cities (Amsterdam, Harbin and Singapore). Besides, the situations both with and without a shading system were simulated for each layout.

6.1. Conclusions

In conclusion, it was found that the optimisation of space layout design can reduce energy demand significantly, especially lighting demand. Besides, the effect of space layouts on building energy performance (BEP) differs between climates. The effect is the highest in the temperate climate and the lowest in the tropical climate. The maximum difference in **lighting demand** is the highest and the highest value happens in Harbin, being 46% without shading and 35% with shading. The maximum difference in **heating demand** is lower, and the highest value happens in Amsterdam, being 11% without shading and 18% with shading. The maximum difference in **cooling demand** is the lowest, and the highest value happens in Amsterdam, being 8% without shading and 11% with shading. As for the **sum of the final energy for heating, cooling and lighting** using an air-source heat pump, the highest maximum difference happens in Amsterdam, being 8% with shading and 8% without shading. The difference in the sum of the final energy is relatively small, as the final energy for lighting makes up a smaller proportion of the total than heating and cooling. The sensitivity analysis shows that WWRs influence the effect of space layouts on lighting demand highly, while slightly on heating and cooling demand. U values have little influence on the effect of space layouts on all energy demand.

6.2. The building physics behind finding the optimal space layout

The study has shown that finding the optimal space layout is not straightforward. Different locations within a layout have different availability of solar radiation and daylighting illuminance, while different functions have different needs in terms of set-points of illuminance, heating and cooling. These needs vary with the occupancy schedule. A good match between available energy and needs results in lower energy demand. Thus, placing the right function in the right location helps to save the energy demand in total. This is the reason why space layout matters for BEP. However, the same location can be the best or worst location for all functions, like the rooms in the middle are best for heating and cooling demand, and corners for lighting demand. There is no space layout where each function is on the location that suits this function best; the best space layout is the result of locating the function that benefits the most from the good locations. Thus, designing a space layout for minimising energy demand is a 'battle' for the best location between functions for who can benefit the most.

6.3. Recommendations for building designers and owners

The results of this study indicate that the space layout helps to reduce energy consumption, and it helps to reach a lower operation cost and a smaller HVAC system, while keeping the same construction cost. However, as explained in the previous paragraph, finding the optimal space layout is a complex process and no simple recommendations like 'locating offices to the South' can be given. In addition, the optimal layout also depends on whether the designer or user prioritises heating, cooling or daylight performance, as the optimal differs depending on the objective. Regarding designing a new building, generally, designers would place functions based on the rule of thumb, like placing offices to the South and canteen to the North. However, this is not the case regarding energy performance. The same location can be the best or worst location for all functions. For instance, the corner is the best for all functions regarding lighting demand and the middle is the best for all functions regarding thermal demand. Generally, designers would think the function with the highest requirements, like the office in this study, should be located in the best location. However, according to the analysis in Section 4.3, the sequence of the greatest difference would show a different most important function, like meeting room for heating demand in both Amsterdam and Harbin. In order to determine the greatest sequence, a computational method is necessary, as it is not easily calculated based on experience.

The effect of space layouts on BEP found in this study is not only suitable for office buildings. As long as the functions in the layout have different needs, like set-points and schedules, the space layout plays an important role in saving energy demand of the whole building, like a complex building with multiple functions, including residential function, office and restaurant, or hospitals. So, when designing these types of building, designers should consider space layout design as a method to improve BEP.

6.4. Recommendations for further research

For the cases investigated, the effect of space layouts on lighting demand is the highest, and the effect on heating and cooling demand is much lower. This could be influenced by the assumed building properties, like thermal mass, set-points, schedule, and shading control. Moreover, the efficiency of the used lighting system also influences the effect of space layouts on BEP. In this paper, a highly energy-efficient lamp was used, while if an energy-inefficient lighting system is used, the effect of space layouts on the lighting demand would be much higher. With the assumed parameters, the effect on the sum of final energy is relatively small, as the difference in lighting demand has less influence on the total than heating and cooling demand. It is therefore recommended to further study the effect of space layouts on BEP given other assumptions for the parameters that highly influence energy performance, like U values, WWRs, lighting efficiency and control types, and shading control types.

Additionally, in this paper, only the locations of functions within the layout with fixed interior partitions were changed, and more studies are needed to test more **design variables of space layout design**, such as space dimensions, space forms, and interior partitions. Furthermore, this study used a fixed layout boundary, while a flexible boundary is expected to provide more good locations for more functions. The effect of space layouts on BEP is expected to be greater than the results shown in this paper if more design variables are included.

6.5. Limitations

There are several factors that could affect the results shown in this paper. The model used in this study does not consider the **surroundings**. The surrounding buildings in the urban context highly influence the amount of solar radiation, daylighting illuminance, and natural ventilation received by different rooms within a layout. The best and worst locations for each energy demand would differ from the ones that are found in this study. Thus, the resulting difference in energy demand between layouts could be highly different from what is found in this paper. This study is conducted within a planar layout, while a **vertical change** in space layouts according to the different vertical conditions resulting from the influence of surrounding buildings would cause a higher difference in energy demand between layouts. Additionally, **natural ventilation** is not considered in the calculation of energy demand. Natural ventilation influences thermal performance highly, especially in summer. Additionally, different orientations of a layout have different conditions of natural ventilation, regarding air pressure, air velocity, and direction. If natural ventilation is included, the difference in thermal demand between layouts would be higher than what is shown in this paper.

Author statement

Tiantian Du: Conceptualization, Methodology, Software, validation, Formal analysis, Writing –original draft preparation.

Sabine Jansen: Conceptualization, Methodology, validation, Formal analysis, Review & editing.

Michela Turrin: Conceptualization, Methodology, Formal analysis.

Andy van den Dobbelsteen: Conceptualization, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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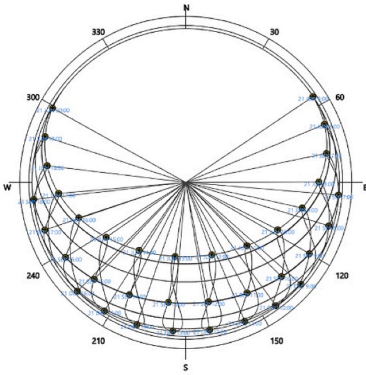
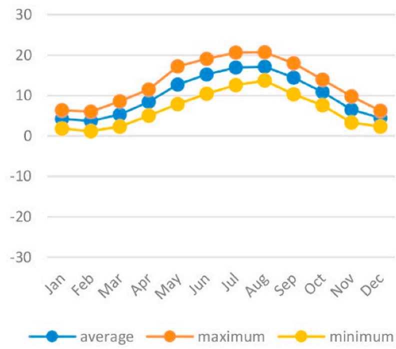
Appendix

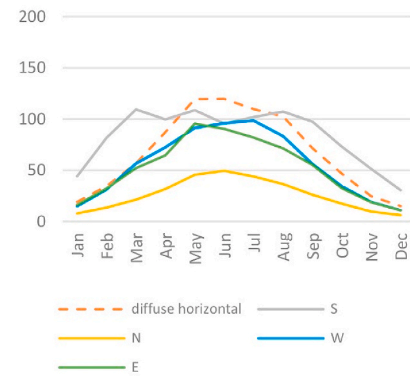
Weather data of the three cities (Amsterdam, Singapore and Harbin).



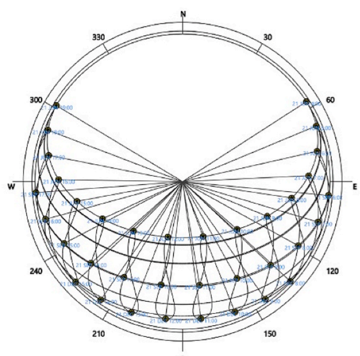
a. Sun path, Amsterdam



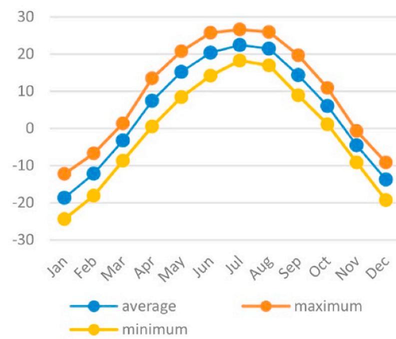
b. Monthly dry bulb temperature (˚C), Amsterdam



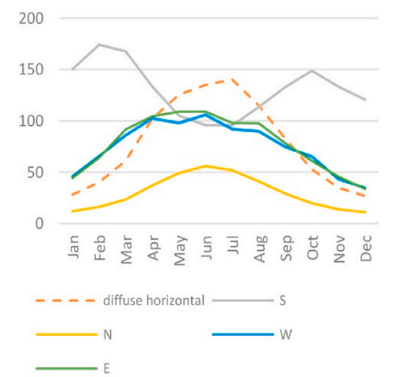
c. Monthly solar radiation (kWh/m2·day), Amsterdam



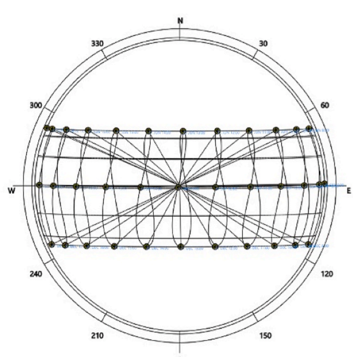
d. Sun path, Harbin



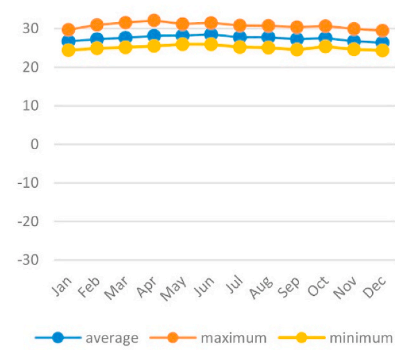
e. Monthly dry bulb temperature (˚C), Harbin



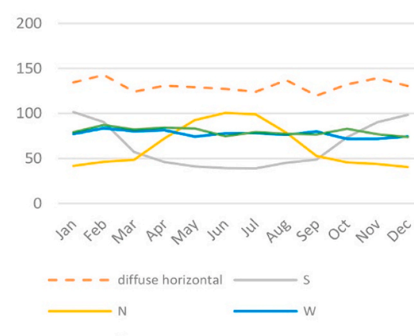
f. Monthly solar radiation (kWh/m2·day), Harbin



g. Sun path, Singapore



h. Monthly dry bulb temperature (˚C), Singapore



i. Monthly solar radiation (kWh/m2·day), Singapore

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