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Impact of space layout on energy performance of office buildings coupling daylight with thermal simulation

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Abstract. Space layout design is one of the most important phases in architectural design, and current studies have shown that it can affect building energy performance. However, its influence has not been quantified. This paper aims at investigating the impact of space layouts on building energy performance. We use the floor plan of an office building in the Netherlands as reference, and propose eleven space layouts based on the reference. Calculations are performed with the tools Honeybee and Ladybug in Grasshopper, which are developed based on Daysim and EnergyPlus, to simulate lighting, cooling and heating demand of these layouts. In addition, we couple daylight with thermal simulation, by importing the artificial lighting schedule calculated in Daysim to EnergyPlus. The result shows that the heating demand of the worst layout is 12% higher than the best layout, the cooling demand of the worst layout is 10% higher than the best layout, and the lighting demand of the worst layout is 65% higher than the best layout. The total final energy use of the worst layout is 19% higher than the best layout.

1 Introduction

Space layout design is one of the design tasks between ‘scheme design’ and ‘design development’ in the early design phase, and it is one of the most important tasks in architectural design [1]. In this paper, architectural space layout is defined as the interior collocation of different spaces, which includes interior layouts, placement of interior walls, and also the geometry of buildings [2]. Studies have shown that there is a great gap between energy-saving potential and available data to aid design in early design phase [3,4]. As one important task in early design phase, space layout is expected to have a high potential of energy saving.

Several studies have tried to evaluate the effects of space layout on energy performance [5–7]. These studies show that space layout can impact energy performance significantly. However, most of these studies mixed space layout with other parameters, for instance occupancy and operation strategy [5], window to wall ratio (WWR) [6], WWR and shading system [8]. This makes it difficult to quantify the impact of space layout based on current research. It is essential to isolate space layout from other parameters to fully understand its effect on energy performance. This study aims at analysing the isolated impact of space layout on energy performance in office buildings.

In this study, we first select a reference office building in the Netherlands. Second, we create eleven variations of layout based on our expectations for extreme situations of heating, cooling and lighting demand. Then, We simulate these layouts, integrating daylight with thermal simulation. We analyse their simulation results and identify the effect of space layout on building energy performance.

2 Methodology

In this study, we use the plug-ins of Ladybug and Honeybee [9] in Grasshopper, which use Daysim [10] and EnergyPlus [11] as simulation engines. Several studies have used these tools, and the results prove their effectiveness in building performance simulation [12,13] The proposed building locates in Amsterdam, the Netherlands, and the used weather data is collected by EnergyPlus [14].

2.1 Reference building and proposed layouts

We select an office building in the Netherlands as reference building. The building and its layout are shown in Fig. 1-2.

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Fig. 1. Photograph of the reference building [15]

Fig. 2. Space layout of the reference building [15]

According to Yeang [16], there are mainly four layout typologies concerning the core location in high-rise office buildings: in the middle, in one side, in two sides, and combined with an atrium. The layout typologies that we use for simulation do not include the layout with an atrium (Fig. 3). Based on the reference building and layout typologies, we propose eleven layouts (Fig. 4). Each layout has 12 rooms, and each room has a size of 9m*9m*3m. The layout width is 36m, and the layout depth is 27m, and the layout area is 972m^2.

Each of the proposed layout has six offices, two meeting rooms, one canteen, one relax room, one core and one staircase. The proportion of different functions will affect the effects of space layout on building energy performance. According to the data collected by U.S. General Services Administration [17], excluding core, circulation and amenities, the space allocation ratio of office buildings is: office constitutes 46~79%, meeting room constitute 8~29%, general and social support space constitutes 14~20%. The space allocation ratio, excluding circulation area, in our layouts is: office constitutes 60%, meeting room constitutes 20%, and canteen and relax room constitute 20%.

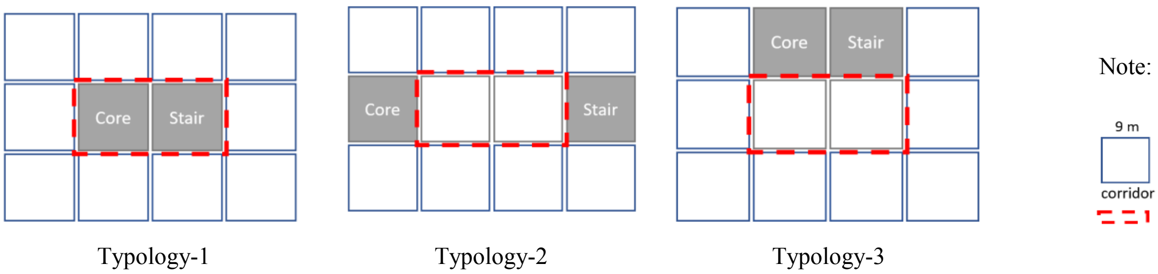
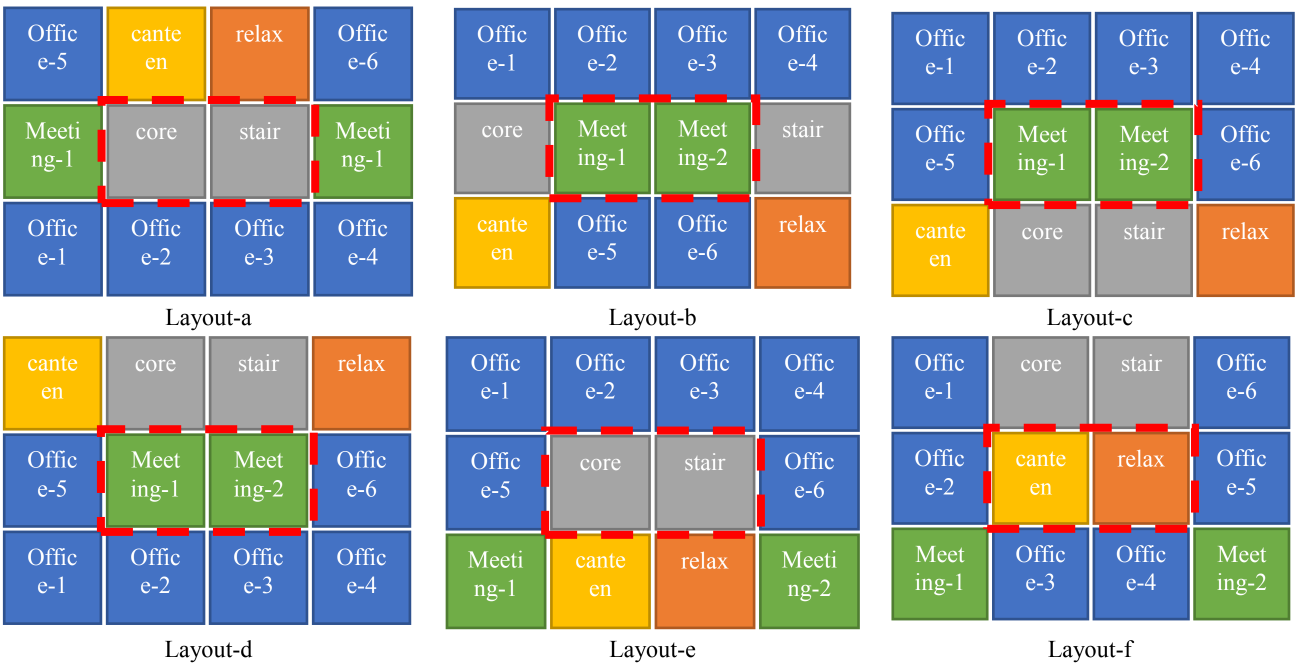


Fig. 3. Typologies of space layout in office buildings



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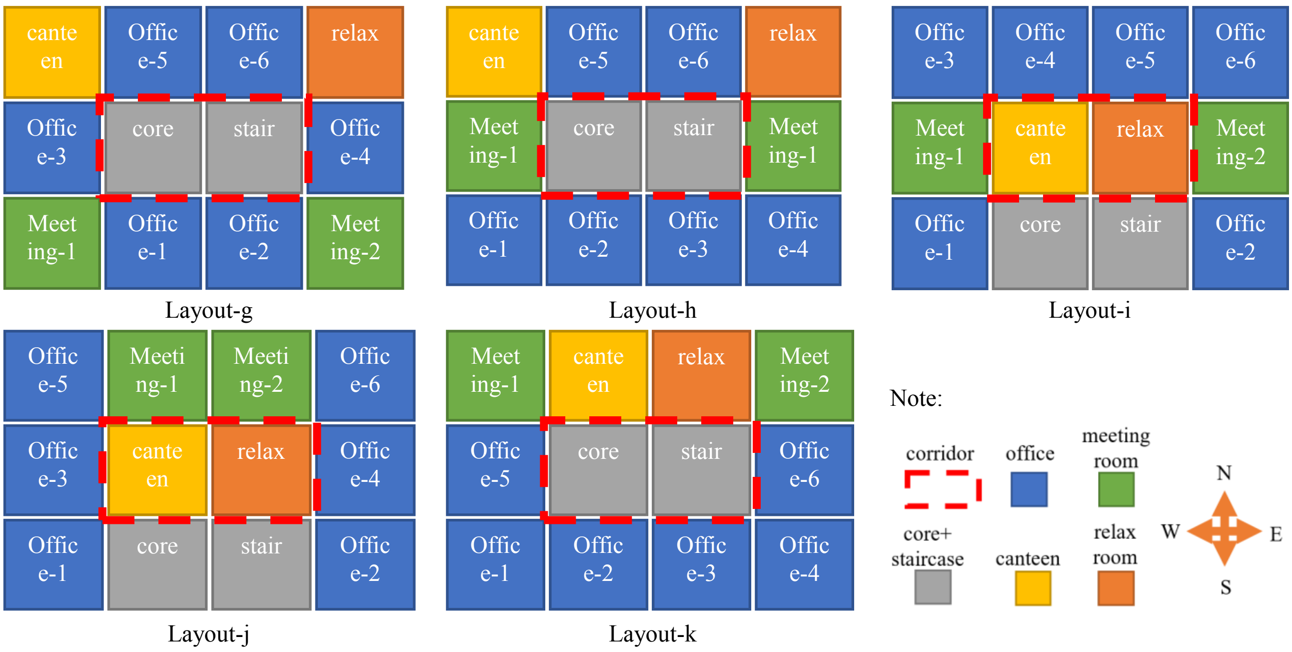

Fig. 4. Eleven layouts used for simulation

2.2 Daylight simulation

In this study, we want to reduce the artificial lighting demand with the supply of daylight. Thus, a workflow that can coupling daylight with thermal simulation is implemented.

2.2.1 Procedure for coupling daylight with thermal simulation

The procedure used to coupling daylight with thermal simulation is as follows: first, input geometry to Radiance and run daylighting simulation; second, a new lighting schedule is generated based on the daylight simulated result, depending on whether the daylight illuminance received at the sensor points can meet the requirements; then, the new lighting schedule is input to EnergyPlus to run energy simulation; finally, we can get the heating, cooling and lighting needs. Lightswitch algorithm is used to calculate artificial lighting schedule in Daysim [18], which determines the lighting schedule based on annual illuminance profile and user occupancy schedule. Among all the sensor points in one lighting zone, the one with the lowest illuminance is used to decide whether artificial lighting is needed.

2.2.2 Control strategy of lighting system

We use the lighting control strategy of 'auto-dimming with switch-off occupancy sensor' [19]. With this control strategy, photocells and occupancy sensors are assumed to be installed in the lighting system. Photocells can control and dim the system until the work plane receives target illuminance. Occupancy sensors can switch off the system if no one is detected. The lighting system has a total standby power of 3 W, and the switch off occupancy sensor has a delay time of 5 minutes.

2.2.3 Target illuminance and materials

As recommended in NEN-EN 12464-1 [20], the target illuminance is 500 lux for offices, and 300 lux for meeting rooms, and 200 lux for canteen and relax room, and 100 lux for core and staircase.

Referring to Jakubiec and Reinhart [21], the materials and simulation parameters used in Daylight simulation are listed in Table 1. For more explanation of parameters of daylight simulation materials, refer to [22].

Table 1. Parameters and materials for daylight simulation

Simulation parameter	**Value**
ab (ambient bounces)	5
ad (ambient divisions)	1024
as (ambient super samples)	16
ar (ambient resolution)	256
aa (ambient accuracy)	0.10
Material	**value**
Floor reflectance	0.20
Ceiling reflectance	0.80
Walls reflectance	0.50
Floor reflectance	0.20
Glazing transmittance	0.76

2.2.4 Windows and sensor points

The WWR in all façades is 40%. The distance from floor to the bottom of windows is 0.8 m. Correspondingly, the distance from floor to work plane is 0.80 m. The height of the windows is 2 m, and all windows are evenly distributed in all facades (Fig. 5). In daylight simulation, the distance between test points is 1 meter. The sensor points used for the calculation of artificial lighting schedule is shown in Fig. 5, which have a distance of 1 meter from the walls.

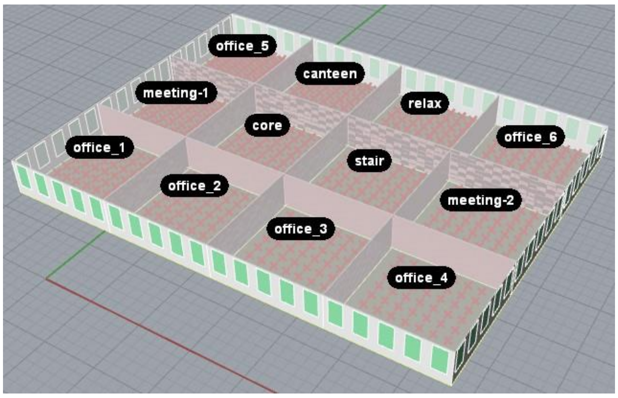

Fig. 5. An example of simulation model with sensor points

2.3 Energy simulation

2.3.1 Materials

The parameters of the materials used in energy simulation are shown in Table 2, which are defined according to the recommendations in the Dutch building decree [23]. The windows have uncoated double glazing with a g-value of 0.7 [24] and a U-value of 1.65 W/m2·K [23]. The floor and ceiling surfaces are defined as adiabatic in simulation, as we assume that this floor locates in the middle of a multi-floors building.

Table 2. Parameters of the material used in energy simulation

	Items	Value	Unit
External wall	U-value	0.16	$W/m^2 \cdot K$
Internal wall	U-value	2.58	$W/m^2 \cdot K$
Interior floor	U-value	1.45	$W/m^2 \cdot K$
Ceiling	U-value	1.45	$W/m^2 \cdot K$
Window	U-value	1.65	$W/m^2 \cdot K$
	g-value	0.7	-

2.3.2 Set-point temperatures for heating and cooling

NEN 16798-1 [25] recommends that the cooling set-point temperature for office, meeting room and canteen is 23~26°C, and the heating set-point temperature is 20~24°C. In this study, we proposed different cooling and heating set-point temperatures for different spaces, as shown in Table 3. The set-back point temperature for heating is 15°C, and it is 30°C for cooling.

Table 3. Set-point temperatures for heating and cooling

Spaces	Cooling set-point (°C)	Heating set-point (°C)
Office	24	22
Meeting room	24	22
Canteen	26	20
Relax room	26	20
Staircase	28	18
Core	28	18

2.3.3 HVAC system

In the simulation, it is not necessary to model a full HVAC system, so we use the ideal loads air system as defined in EnergyPlus [26]. In this system, the air supplied to a zone for heating or cooling has sufficient quantity which can meet the requirement. The ventilation flow rate per area is 0.03 $m^3/s \cdot m^2$ which is constant, and the ventilation flow rate per person is 0.00889 $m^3/s \cdot$person which varies with different functions. The system has the sensible heat recovery with an effectiveness of 0.7. An air side economize is also used, which increases ventilation when the cooling demand is high. The air flow rate for infiltration is 0.2 ACH [24]. The threshold of humidity is 25%-60%, as recommended in prEN 16798-1 B2.2 [25].

2.3.4 Internal gains

The maximum numbers of people in different spaces at peak time are shown in Table 4, which are decided based on the data that are collected from some real estate websites, e.g. [27]. In Daysim, the ‘ideal lighting system’ is used, in which it is assumed that the target illuminance can be delivered when the lighting system is fully switched on [28]. For this simplified calculation, the installed lighting power for each zone is needed. A new generation of linear fluorescent T5 lamps is assumed to be used in the lighting system, which is energy efficient with lower costs and its luminous efficacy is 90 lm/W. According to Annex 45 [29], the installed power densities for required illuminance in different spaces are listed in Table 4. The equipment load density of difference functions used in the simulation, as shown in Table 4, is assigned according to the data collected by US Department of Energy for Commercial Reference Buildings [30].

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Table 4. Parameters of internal gains

Spaces	Max occupancy (person)	Max lighting power density (W/m^2)	Max equipment load density (W/m^2)
Office	6	11	6.9
Meeting room	12	8	4
Canteen	9	5	48
Relax room	9	5	0.8
Staircase	3	2	0
Core	3	2	3

2.3.4 Schedules

The occupancy and equipment schedules for different functions are shown in Fig. 6. We assume that there are two hours in the morning and afternoon respectively during which the meeting rooms are occupied. At noon, people leave offices and stay in canteen and relax room. The average occupancy schedule of offices for one day is around 0.3, which is the same as in the Dutch UNIEC tool and what is reported in NTA 8800 [31].

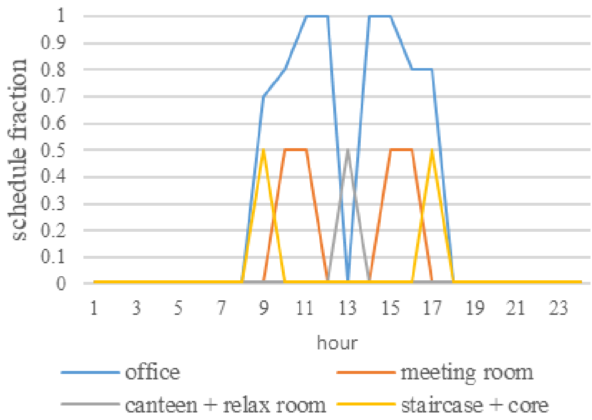

Fig. 6. Occupancy and equipment schedules for different functions

3 Results

3.1 Simulation result

The eleven layouts are simulated with all the settings as shown formerly, and the final energy balances are shown in Table 5Table . The heating, cooling demand and lighting gains are compared, and we assume that the lighting gains equals to the lighting demands. In total, the heating demand of the worst layout for heating is 12% higher than the best layout, and the cooling demand of the worst layout for cooling is 10% higher than the best layout, and the lighting demand of the worst layout for lighting is 65% higher than the best layout. This indicates that space layout design can help to decrease lighting demand significantly.

Table 5. Energy balances of eleven layouts (kWh/m^2)

	Heating demand	Cooling demand	Lightin g gains	Solar gains	Equip gains	People gains	Infiltration losses	Vent losses	Opaq losses	Glaz losses	Thermal storage
layout-a	16.6	-15.2	5.3	53.4	10.9	15.1	-18.6	-26.4	-2.9	-35.9	-2.0
layout-b	15.5	-13.9	8.1	53.4	10.9	15.1	-20.2	-27.0	-3.0	-36.3	-2.5
layout-c	15.0	-13.9	8.7	53.4	10.9	15.1	-20.5	-26.4	-3.0	-36.7	-2.5
layout-d	16.2	-14.3	7.4	53.4	10.9	15.1	-19.8	-27.8	-2.9	-35.7	-2.4
layout-e	15.7	-15.1	6.6	53.4	10.9	15.1	-19.0	-26.1	-3.0	-36.4	-2.1
layout-f	16.4	-14.7	5.9	53.4	10.9	15.1	-19.3	-26.7	-2.9	-35.6	-2.5
layout-g	16.1	-15.3	7.2	53.4	10.9	15.1	-18.9	-27.3	-3.0	-36.3	-2.0
layout-h	16.3	-15.1	6.2	53.4	10.9	15.1	-18.8	-26.8	-3.0	-36.2	-2.0
layout-i	15.7	-14.0	5.7	53.4	10.9	15.1	-19.8	-25.2	-3.0	-36.3	-2.5
layout-j	16.0	-14.1	5.7	53.4	10.9	15.1	-19.8	-25.5	-3.0	-36.3	-2.5
layout-k	16.8	-15.3	5.5	53.4	10.9	15.1	-18.7	-26.8	-2.9	-35.9	-2.0
Note : Equip gains - equipment gains, ven losses – mechanical ventilaiton losses, opaq losses - opaque Conduction losses, glaz losses - glazing Conduction losses											

3.2 Result analysis

3.2.1 Lighting demand

The result of lighting demand for these layouts is aligned with what could be expected:

- layout-a and layout-k have the lowest demand, as in the two layouts most offices face the south and meeting rooms face the east and west;
- layout-c has the highest lighting demand, as both meeting rooms locate in the middle without external windows, and most offices face the north.

3.2.2 Heating demand

Layout-c has the lowest heating demand, and layout-k has the highest heating demand, although the difference is relatively small. In order to analyse their difference, their monthly energy balances in winter is compared in Fig. 7. It is apparent that the difference of heating demand between layout-c and layout-k is mainly caused by the difference of lighting gains, in which layout-k needs much less artificial lighting than layout-c, leading to lower internal gains while having similar solar gains.

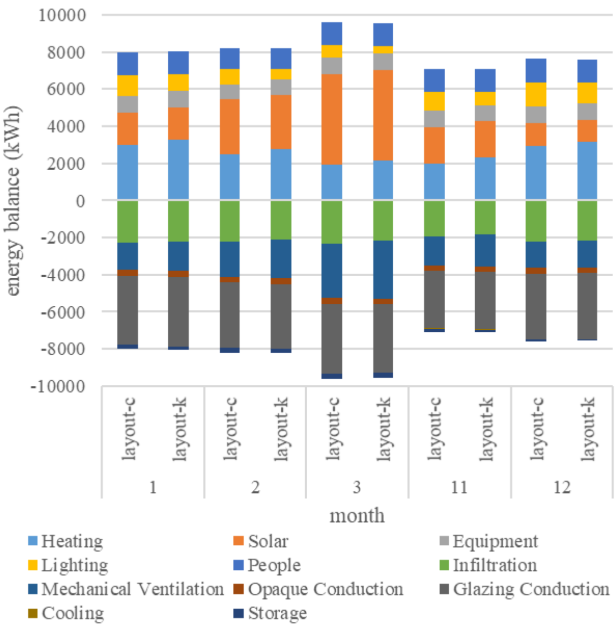

Fig. 7. Monthly energy balance (kWh) comparison of layout-c and layout-k in winter

3.2.3 Cooling demand

Layout-g and layout-k have the highest cooling demand, and layout-b and layout-c have the lowest cooling demand. Offices have highest requirement of summer comfort and also the highest internal gains. In layout-b and layout-c, most of offices are located in the north side, where has much less solar gains. The energy balance on June 7 of office-2 in the north of layout-c and the office-2 in the south of layout-k are compared in Fig. 8 and Fig. 9. June 7 has the highest average temperature and is also a sunny day. Comparing Fig. 8 and Fig. 9, it is apparent that during the period when cooling is needed, the solar gains are the main cause of the difference of cooling demands between these two offices. If most of offices are located in the orientation with more daylight, the layout can have higher cooling demand.

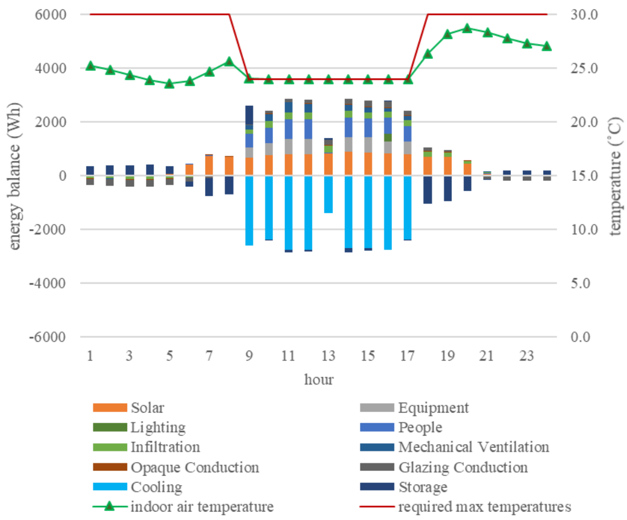

Fig. 8. Energy balance (Wh) of office-2 in layout-c, on June 7

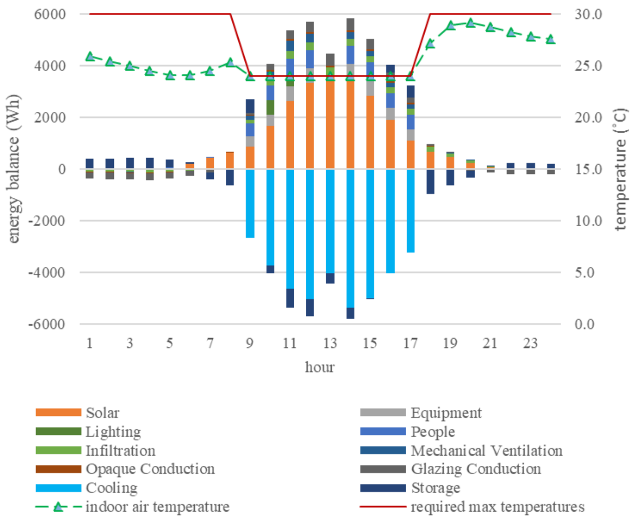

Fig. 9. Energy balance (Wh) of office-2 in layout-k, on June 7

3.2.4 Relation between heating, cooling and lighting demand

Based on the result and analysis, orienting the rooms with high lighting requirements (e.g. office and meeting room) towards the facades with less daylight results in higher demands for artificial lights. This also results in lower heating demand, although the effect on heating is much smaller. The cooling demand is also lower, as there is less solar gains in summer. For most layout, the layouts with higher heating demand also have higher cooling demand, according to the result shown in Table 5.

3.2.5 Final energy use

In order to assess the relative importance of each aspect, the demands cannot be simply added up, as they refer to different types of energy: heating and cooling are the demand for thermal energy, and lighting is electricity use. For comparison, all energy demands must be converted to final energy use. Therefore, the final energy uses for heating, cooling and lighting are compared in Table 6, in which we assume that the COP is 4 for heating system, and 3 for cooling systems, and 1 for lighting system. Layout-i has the lowest final energy use, and layout-c has the highest final energy use, and the later one is 19% higher than the former one. The effect of space layout on building final energy use is greater than the energy demand, as the lighting energy use constitutes a much larger proportion, and space layouts can affect lighting use the most.

Table 6. Final energy use comparison for eleven layouts (kWh/m^2)

	final energy use for heating	final energy use for cooling	final energy use for lighting	Total final energy use
layout-a	4.1	5.1	5.3	14.5
layout-b	3.9	4.6	8.1	16.6
layout-c	3.8	4.6	8.7	17.1
layout-d	4.1	4.8	7.4	16.3
layout-e	3.9	5.0	6.6	15.6
layout-f	4.1	4.9	5.9	14.9
layout-g	4.0	5.1	7.2	16.3
layout-h	4.1	5.0	6.2	15.3
layout-i	3.9	4.7	5.7	14.3
layout-j	4.7	5.7	10.4	14.4
layout-k	5.1	5.5	10.6	14.8

4 Conclusion and discussion

In conclusion, space layout can affect lighting demand significantly, up to 65%, and can affect heating and cooling demand each to around 10%. Additionally, the heating and lighting demands are interrelated: more lighting demands lead to less heating demands.

The effect on final energy use depends not only on the demand but also on the efficiency of the energy systems. Assuming that COP is 4 for heating and 3 for cooling, it can affect the final energy use significantly. More research should be conducted to fully detect its effect, and designers and architects should consider energy performance in space layout design, especially for the lighting demand. For now, we only studied the layouts with fixed perimeter, but if the building's geometry is included, the effects will be much larger. The shape of these eleven layouts is rectangle, and it is necessary to test other shapes, e.g. U shape, T shape and L shape. In addition, this case study is assumed to locate in temperate climate, and other climates should also be detected.

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