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Review

Effects of Architectural Space Layouts on Energy Performance: A Review

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Abstract: As one of the most important design tasks of building design, space layout design affects the building energy performance (BEP). In order to investigate the effect, a literature review of relevant papers was performed. Ten relevant articles were found and reviewed in detail. First, a methodology for studying the effects of space layouts on BEP were proposed regarding design variables, energy indicators and BEP calculation methods, and the methodologies used in the 10 articles were reviewed. Then, the effects of space layouts on energy use and occupant comfort were analysed separately. The results show that the energy use for heating, cooling, lighting and ventilation is highly affected by space layouts, as well as thermal and visual comfort. The effects of space layouts on energy use are higher than on occupant comfort. By changing space layouts, the resulting reductions in the annual final energy for heating and cooling demands were up to 14% and 57%, respectively, in an office building in Sweden. The resulting reductions in the lighting demand of peak summer and winter were up to 67% and 43%, respectively, for the case of an office building in the UK, and the resulting reduction in the air volume supplied by natural ventilation was 65%. The influence of other design parameters, i.e., occupancy and window to wall ratio, on the effects of space layouts on BEP was also identified.

Keywords: space layout; building energy performance; energy-efficient design

1. Introduction

Architectural design highly affects the building energy performance (BEP), and energy-efficient design is therefore often studied [1]. Space layout design is one of the most important tasks in architectural design, taking place around the stages of 'scheme design' and 'design development' in the early design phase [2,3]. In this paper, the architectural space layout is defined as the allocation of different spaces, and it is decided based on the placement of interior partitions as well as exterior walls. The design variables of space layout design include function allocation, space dimension (width, length, height), space form, interior partition and interior opening. Moreover, the layout boundary can also be the design variables of the space layout design with a non-fixed boundary as a consequence of changing interior and exterior walls. These will be explained in more detail in Section 3.1.1.

There are plenty of studies exploring the effects of geometry on BEP, such as the studies on boundary dimensions [4–8], forms [9–12] and orientations [4,5,13]. Most studies have been reviewed in [1]. These studies imply that space layouts affect BEP greatly, as geometry can be a consequence of the space layout design within a non-fixed layout boundary. Moreover, different functions have different comfort requirements such as thermal comfort and lighting levels, which result in different internal gains. Hence, if spaces can be mapped to the proper orientations and locations that have sufficient daylight and natural ventilation within a building, the building is expected to require less energy demand in total.

Although architectural space layout is expected to highly affect BEP, it is rarely included in the studies on energy-efficient building design. Numerous studies exist on energy-efficient design, and most of them focus on geometry [11,14], envelope [15,16], façade [17,18], material [19,20], atrium [21,22] and shading systems [23,24]. On the other hand, researchers have been working on space layout design for decades [25,26]; however, they mainly focused on other design objectives rather than energy performance. These objectives include safety [27,28], logistics [29,30], efficiency [31,32], finance cost [33,34], occupant health and performance [35,36], view connection [37,38] and acoustics [39,40]. These two research domains, space layout design and energy-efficient building design, are shown in Figure 1. The overlapping area of the two domains, i.e., energy-efficient space layout design, is the focus of this paper. This paper aims at the effects on BEP caused by changing space layouts, without considering the possible influence on the indirect cost of the building, such as space usability and workability.

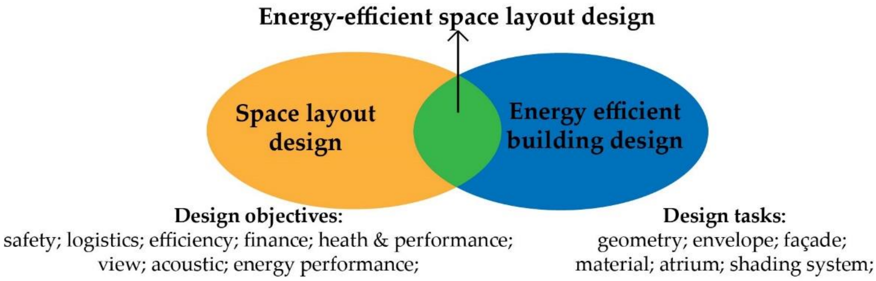


Figure 1. Relevant research domains.

The review was performed by searching in engines of Google Scholar, ScienceDirect, Web of science and the library of the Delft University of Technology. The keywords used to search the relevant references include two types of terms: space layout and energy, as shown in Table 1. Moreover, we limited the discipline to architectural design.

Table 1. Keywords for searching references.

Terms (Space Layout)		Terms (Energy)
Space layout Space planning Space allocation Interior layout Floor plan	and	Energy use Energy consumption Energy performance Energy saving Heating Cooling Lighting Ventilation

The paper is structured as follows: first, as background, the mechanism for how space layouts affect BEP is formulated. Second, the methodology for studying the effects of space layouts on BEP is proposed as the guideline to review each relevant article; then, the procedure for reviewing one article is shown as an example and each article is reviewed following the same procedure. Next, the methodologies used in the relevant articles are analysed and compared. Third, the effects of space layouts on energy use and occupant comfort are identified and analysed separately.

2. Mechanism for How Space Layouts Affect BEP

It is important to analyse the mechanism for how space layouts affect BEP before the detailed review. Based on the studies found with the keywords of space layout terms and energy terms, we identify the following factors that determine how space layouts affects BEP below.

2.1. Different Occupancy and Comfort Requirements Between Functions

Different layouts accommodate different occupant densities. For instance, an open office has a higher occupant density than a cellular office [41,42]. Space layouts also affect the occupant behaviour, such as attending an activity or changing the location where the activity happens, as shown in [43]. Different occupancy has different internal gains and also different requirements for comfort purpose, such as the total amount of ventilation. Eventually, the different occupancy affects the energy demand. Additionally, different functions have various levels of comfort requirements. For instance, as shown in the Dutch standard of NEN 16798-1 [44], the minimum operative temperature for space heating is 20 °C for sedentary activity like in offices, while the value is 16 °C for standing-walking activity like in corridors. As recommended in [45], the illuminance set-point is 500 lux for offices and 300 lux for meeting rooms, while the value is 200 lux for canteens and 150 lux for staircases. Thus, different comfort requirements between functions affect the whole energy demand eventually.

2.2. Daylighting

The effect of daylighting can be explained with the following three points. First, different layouts import different levels of daylight into the building. This is proven by the studies on the daylighting performance of the building with atriums [46–48] and courtyards [49]. These studies show that by changing the shape, location and dimension of atriums or courtyards, the daylighting performance of the whole building changes. Secondly, an appropriate space layout combined with the glazing design boosts the application of daylight within a building. For instance, the function with a higher lighting requirement can be located near the south façade for more solar radiation, and the function with a lower lighting requirement can be located in the middle or near the north façade to make a concession for other spaces, in the Northern Hemisphere. Thirdly, the interior partitions also affect the application of daylight, considering the visual comfort of occupants, as shown in [50].

2.3. Natural Ventilation

By combining with openings, an appropriate space layout distributes fresh air to the rooms based on their demands. For instance, the function with higher occupancy can be located near the windward façade and the function with a lower ventilation requirement, like a storage or facility room, can be located near the leeward façade. The study of [51] shows that by changing the shape of interior partitions for corridors, a higher mean flow velocity can be obtained, increasing up to 33%, as well as a steadier airflow within the building. Moreover, by changing the location and dimension of buffer spaces, such as a courtyard [52], solar chimney [53], atrium [54] and light-well [55], the natural ventilation within buildings changes significantly. The study of [56] showed that the building with a better space connection and integration has a higher natural ventilation velocity. For instance, the corridor and dining room have high permeability and accessibility, and the measured data shows that they also have higher ventilation velocities. Another study [57] showed that a vernacular building with courtyards, patios and gardens has a better microclimate than a modern building without buffer spaces, in term of air temperature, relative humidity and wind velocity.

2.4. Control of the Heating, Cooling, Ventilation and Lighting System

Different space layouts are suitable for different types of control for space heating, space cooling, ventilation and lighting systems. For instance, the individual control is more suitable for a cellular office than an open office, as shown in [58,59]. The blind control is more difficult in an open office than in a cellular office, as shown in [60]. Different control types result in different energy performance. Moreover, the indicators relevant to daylighting and natural ventilation can be used as indicator for controlling, for instance, the availability of daylight for lighting system control [61] and air quality and thermal comfort for ventilation system control [62]. Using dynamic control based on the available daylight and natural ventilation, the effects of space layouts on BEP are boosted.

Table 2. Collection of the studies focusing on the effects of space layouts on building energy performance (BEP).

Ref.	Author	Year	Location	Climate	Building Type	Floor Area (m^2)	Constant Parameters	Design Variables	Energy Indicators (Unit)	BEP Calculation Period	BEP Calculation Tools	Multi-Domain Integration	Resulted Biggest Reduction
[42]	**Musau & Steemers**	2008	Garston, the UK	Cfb	office	144 (1 floor)	boundary dimension, form and orientation, heating and cooling set-points, WWR, material, opening for ventilation, occupancy schedule	function allocation, interior partition, lighting and ventilation requirements, occupancy, number and distribution of workstations	heating demand (kWh/day) cooling demand (kWh/day) lighting demand (kWh/day)	peak winter and summer day	-lighting: Lightscape -thermal: TAS -natural ventilation: TAS	daylight + thermal; natural ventilation + thermal;	H: 57% C: 11% L (winter): 43% L (summer): 67%
[63]	**Musau & Steemers**	2009	Garston, the UK	Cfb	Office	144 (1 floor)	Same as in [42]	closed or opened doors, state of opening windows, the others are the same as in [4]	air volume from natural ventilation (m^3)	peak winter and summer day	-lighting: Lightscape -thermal: TAS -natural ventilation: TAS	Same as in [42]	AV: 65%
[64]	**Souza & Alsaadani**	2012	London, the UK	Cfb	office	658 (1 floor)	boundary dimension, form and orientation, material, WWR	function allocation, interior partition, air exchange rate, internal gains	heating demand (kWh/m^2 a) cooling demand (kWh/m^2 a)	One year	EnergyPlus	No	H: 52% C:24%
[65]	**Poirazis et al.**	2008	Gothenburg, Sweden	Dfb	office	6177 (6 floors)	boundary dimension, form and orientation, occupancy schedule, material, infiltration rate	function allocation, interior partition, occupancy, lighting power density, illuminance requirement, equipment power density, ventilation rate, WWR	final energy for heating (kWh/m^2 a) final energy for cooling (kWh/m^2 a) final energy for lighting (kWh/m^2 a)	One year	IDA ICE 3.0 [66]	No	H:14% (30% WWR) C: 57% (30% WWR) L: 4.1 kWh/m^2 a (40% WWR)
[67]	**Dino & Ucoluk**	2017	Ankara, Turkey	BSk	library	7200 (4–8 floors)	material, internal gains from equipment, occupancy schedule	function allocation, interior partition, WWR, boundary dimension and form	heating demand (kWh/day) cooling demand (kWh/day) lighting demand (kWh/day) Illuminance set-point satisfaction	four seasonal days	OpenStudio (EnergyPlus)	No	H: 19% C: 20% L: 10% IS: 27%
[68]	**Yi**	2016	Seoul, South Korea	Dwa	Office	936 (1 floor)	boundary dimension, form and orientation, material, occupancy schedule	function allocation, interior partition, WWR	PMV Indoor daylighting level (daylight illuminance, lux) shading level	One year	Ecotect (no longer available)	No	PMV: 13% DL: 11% SL: 2%
[69]	**Rodrigues et al.**	2014	Coimbra, Portugal	Csb	apartment	141–163 (1 floor); 158–189 (2 floors)	Material, schedule, occupancy, internal gains	boundary dimension and form, function allocation, interior partition, WWR, type and size of shading system	thermal discomfort penalty based on air temperature (°C)	One year	EnergyPlus	No	TDP: 33% (1 floor), 29% (2 floors)
[70]	**Dogan et al.**	2014	/	/	/	/	Boundary dimension, form and orientation, material, internal gains	inter zone heat flows	heating demand (/) cooling demand (/)	One year	No mention	No	/
[71]	**Baušys & Pankrašovaite**	2005	/	/	/	136-214 (minimal: 119, 1 floor)	Material, occupancy, schedule	function allocation, interior partition, WWR	final energy of heating (/) final energy of lighting (/)	One year	Steady state calculation	Daylight + artificial lighting	/
[33]	**Michalek et al.**	2002	/	/	/	165 (minimal, 1 floor)	boundary dimension, form and orientation, material, internal gains	function allocation, interior partition, WWR	final energy of lighting (/) final energy of heating (/) final energy of cooling (/)	One year	Steady state calculation (based on recommendation of ASHRAE)	Daylight + artificial lighting	/

Note: '/': the information is not shown in the reference. WWR: window to wall ratio; HVAC: heating, ventilation and air conditioning; PMV: predicted mean vote; ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers; TAS: Thermal Analysis Software; IDA ICE: IDA Indoor Climate and Energy; H: heating demand or final energy; C: cooling demand or final energy; L: lighting demand or final energy; AV: air volume from natural ventilation; IS: illuminance set-point satisfaction; DL: indoor daylight level; SL: shading level; TDP: thermal discomfort penalty. The tested climates are identified based on the Köppen-Geiger climate classification as shown in [72]. Cfb: Temperate oceanic climate; Dfb: Humid continental climate; BSk: Cold semi-arid climate; Dwa: Humid continental climate; Csb: Temperate Mediterranean climate.

3. Methodology for Studying the Effects of Space Layouts on BEP

There are plenty of studies that only studied the effects of geometry (such as boundary dimensions, building forms and orientations) on BEP without changing interior layouts. They are not included in the detailed review below, and the following detailed review is limited to the studies that also changed interior layouts. Ten articles were found focusing on the intersection of space layouts and energy performance, as shown in Table 2. First, in Section 3.1, a methodology for how to study the effects of space layouts on BEP is proposed, which was used as the guideline for reviewing the 10 articles. Then, the procedure for reviewing one article is shown as an example, and the other articles were reviewed following the same procedure. It is unnecessary to show the procedures for all articles, as similar procedures were used. After that, the 10 articles were reviewed following the same procedure as shown in Section 3.2 and their methodologies are analysed and compared in Section 3.3. Moreover, the resulting effects of space layouts on BEP derived from the 10 articles are analysed and compared in Sections 4 and 5.

Following the methodology proposed in Section 3.1 and the example procedure in Section 3.2, the 10 articles were reviewed in terms of climates, building types, floor areas, constant parameters, design variables, energy indicators, BEP calculation method, BEP calculation tools, multi-domain integration and resulted biggest reduction. All this information is shown in Table 2. In order to quantify the effects of space layouts on BEP, the term of reduction (%) was used, referring to the highest value minus the lowest value, and divided by the highest value. The reduction means the percentage of the studied indicator that the best layout reduces compared to the worst layout. The values shown in the column of the resulting biggest reduction in Table 2 are based on the analysis in Sections 4 and 5.

3.1. Proposed Methodology for Studying the Effects of Space Layouts

Based on the methodologies used in the 10 articles (Table 2) and also the mechanism for how space layouts affect BEP, a methodology is proposed for systematically studying the effects of space layouts on BEP. It is also used as the guideline to review and analyse the 10 articles.

3.1.1. Design Variables

In order to analyse the isolated effects of space layouts, the design variables influencing energy balance are classified, regarding their relationships with space layouts, as shown in Table 3. Firstly, the design variables belonging to space layouts include function allocation, space dimension, space form, interior partition and interior opening [33,42,68,73]. Secondly, if space layouts are designed within a non-fixed layout boundary, the boundary dimension, form and orientation can also be changed consequently [69,74]. Thirdly, the space properties that influence BEP include functional requirements and the use of spaces: functional requirements mean that if different functions are located in different spaces, they have different requirements for heating, cooling, lighting and ventilation; the use of spaces refers to the profiles of internal gains resulting from occupants, lighting, appliances, etc. Lastly, the envelop design of buildings is important for BEP, and it influences the effects of space layouts on BEP. A systematic methodology for studying the effects of space layouts on BEP should first keep the other design variables constant and only change the design variables of space layouts in order to assess the isolated effects of space layouts on BEP, and after this, by adding the other design variables one by one, evaluate their influence on the effects of space layouts.

Table 3. Classification of design variables affecting BEP, regarding their relationship with space layout design.

Design Variables of Space Layouts (with a Non-Fixed Boundary)		Space Properties		Envelope Design
Space layout design (within a fixed boundary)	• Boundary dimension • Boundary form • Orientation	**Functional requirements**	**Use of spaces**	• Thermal transmittance • Window area • Window location • Glazing type • Shading type and effectiveness • Air tightness
• Function allocation • Space dimension • Space form • Interior partition • Interior opening		• Set-point temperature for heating • Set-point temperature for cooling • Lighting requirements (e.g., illuminance) • Ventilation requirement (e.g., air flow rate) • Control types	• Occupancy, activity and schedule • Internal gains from appliances and lighting • Opening state of windows and doors	

Note: 'Function allocation' means allocating different functions to different rooms. 'Control types' means the different types of the control for lighting, ventilation, heating and cooling systems. 'Appliances' include the used devices, equipment and machines.

3.1.2. Energy Indicators

Energy indicators differ in three ways: energy end-use, assessment period and system boundary. They are classified and explained below:

- The energy end-use in buildings include space heating, space cooling, water heating, lighting, ventilation, electricity for appliances, etc. [75]. The more energy end-use is included, the more exhaustive the resulted effects of space layouts are.
- Regarding the assessment period, energy can be calculated on an annual basis or for a shorter time period, like a summer day and a winter day. The assessment period is decided depending on the located climate zone. For instance, if the heating demand is dominant compared to the cooling demand in one climate, the heating period is more representative and the BEP calculation should be calculated at least for the heating period.
- There are different system boundaries for the BEP assessment, including the conditioned space perimeter of a building or building unit, building site, and outside building site [75]. The corresponding energy inputs regarding the system boundaries are energy demand (or energy needs), final energy and primary energy, respectively, as shown in Figure 2. The used assessment boundary should be clearly stated.

Figure 2. Different boundaries for BEP assessment, adapted from [76].

3.1.3. BEP Calculation Methods

The way in which the space layout affects BEP highly depends on how daylighting and natural ventilation is used in buildings. Thus, in order to assess the effect, the BEP calculation with multi-domain integrations is necessary, like integrating daylighting and natural ventilation with energy assessment. Moreover, the type of BEP calculation methods highly influences the accuracy of BEP results.

- **Multi-domain integrations for BEP calculations**: As mentioned in Section 2, the daylighting and natural ventilation in buildings is highly affected by space layout design. The possible multi-domain integrations include calculating the reduction of artificial lighting as a result of the available daylighting and calculating the reduction of mechanical ventilation as a result of the available natural ventilation. The possibility of integrations depends on whether the located climate zone prefer daylighting or natural ventilation. Integrating multi-domain influences is also needed to accurately predict BEP for building simulations, as shown in [77]. However, no single simulation tool can simulate all physical domains accurately, thus, exchanging information between different simulation software across multi-domains is needed, as shown in [78,79]. Some tools can help to do this, such as a functional mock-up unit in EnergyPlus [79] and a co-simulator for TRNSYS and ESP-r [80].
- **Types of BEP calculation methods**: There are mainly two different types of BEP calculation methods: the steady-state calculation and the dynamic simulation. The steady-state calculation, in principle, is based on energy balance without considering dynamic effects for a given moment [81]. It can also be used for a long time, like one month or a whole season, by taking into account the dynamic effects with empirically determined gain and loss utilisation factors. The dynamic simulation calculates energy balance with a short time step, typically 15 min or one hour, taking into account the heat

stored in and released from the mass of buildings. The steady-state method does not take into account or roughly calculate the dynamic response of the building thermal mass, and its results are less accurate. National norms are usually based on the steady-state method. A large number of tools are available for dynamic simulation nowadays, such as TRNSYS [82], EnergyPlus [83], IDA Indoor Climate and Energy (IDA ICE) [66], ESP-r [84], and Clim2000 [85].

3.2. An Example of the Review Procedure for Each Article

The 10 articles in Table 2 are reviewed systematically following the proposed methodology shown in Section 3.1. The methodologies of previous articles analysed in Section 3.3 and the results shown in Sections 4 and 5 are fully based on the systematically review of the 10 articles. In order to explain how each article is reviewed, an example of the procedure for reviewing one article is presented in this section. The other articles are reviewed following the same procedure as shown in this example. In order to avoid unnecessary similar content, the review procedures of the other articles are not presented.

The study of Musau and Steemers [42] is taken as an example, as it provided detailed information on energy simulation and clear results. This article investigated the energy demand for heating, cooling and lighting with five different office layouts in Garston, the UK, in a temperate oceanic climate (Cfb). The five layouts are Hive (open plan), Den, Club, Combi and Cell, as shown in Figure 3. Occupancy differs between layouts. We extract the following information from the original article, following the methodology shown in Section 3.1, in order to identify the isolated effects of space layouts.

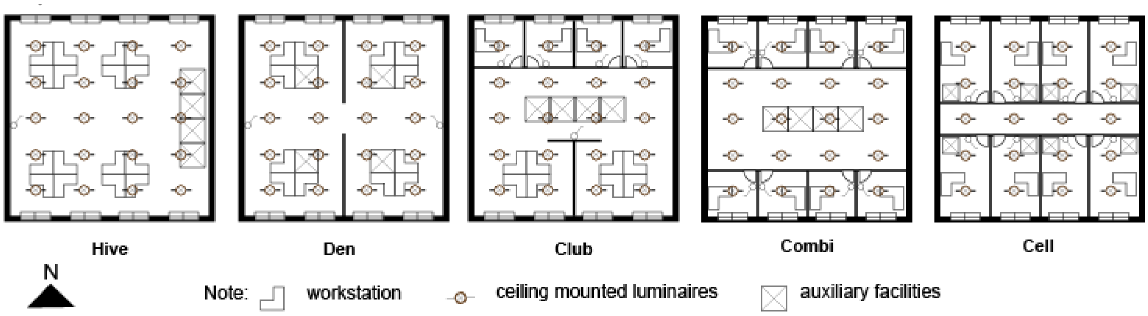


Figure 3. Five layouts with a boundary of 12 m × 12 m in [42].

3.2.1. Identifying Design Variables

In order to identify the isolated effects of space layouts, each article needs to be analysed and selected for the cases which only changed the design variables of space layout design while keeping the other variables, such as materials and window to wall ratio (WWR), constant. Regarding the design variables influencing BEP as shown in Table 3, the following variables were changed in this article:

- **Space layout design:** function allocation and interior partition.
- **Functional requirements:** lighting and ventilation requirements. The used control types of lighting and ventilation systems were related to the distribution of occupants. For instance, when a room had no occupants, the lighting and ventilation supply was reduced to the lowest level. Different layouts had different distributions of occupants, resulting in different requirements for lighting and ventilation.
- **Use of spaces:** occupancy and number of workstations. Different layouts had different numbers of occupants and workstations.

3.2.2. Identifying Constant Parameters

Except for design variables, it is also necessary to identify the constant parameters used in each article, in order to compare the results from different articles. Regarding the design variables influencing BEP as shown in Table 3, the following design parameters were kept constant in this article:

- **Layout boundary:** boundary dimension, boundary form and orientation.
- **Functional requirements:** temperature set-points for heating and cooling.
- **Use of spaces:** occupancy schedule.
- **Envelope design:** WWR (30% for the north and south façade, and 0% for the east and west façade), materials (including the reflectance and conductance of roofs, floors and external walls) and size and location of openings for ventilation (800 mm wide door shutters at the bottom of each door).

3.2.3. Identifying Energy Indicators and the BEP Calculation Method

Energy indicators need to be identified for each article, in order to classify the resulting effects of space layouts from different articles. The used BEP calculation method in each article influences the accuracy of results. In this article, the used indicators include heating demand, cooling demand and lighting demand in the peak winter (21st of December) and peak summer (12th of July). This study was performed with dynamic simulation, using Thermal Analysis Software (TAS) for energy and natural ventilation simulation and Lightscape for daylighting simulation. The effects of daylighting and natural ventilation were integrated with energy simulation. The required artificial lighting was reduced based on the daylighting simulation result, and the required mechanical ventilation was reduced based on the natural ventilation simulation result, and these were used as inputs into the energy simulation.

3.2.4. Selecting Cases and Analysing Results

Most articles present multiple cases and some of them mixed the design variables of space layouts with other variables. In order to identify the isolated effects of space layouts, the cases in each article should be strictly selected. Among all cases presented in this article, we selected and compared only the cases with the same number of occupants. The results of the cases with the same occupancy are reorganised and shown in Table 4. Table 4 shows the isolated effects of space layouts as well as the influence of occupancy, as follows:

- **Isolated effects of space layouts:** The heating demand differs highly between layouts with low occupancy. The biggest reduction in the heating demand is 57%, which is between the layouts with six occupants. In contrast, the reduction in the cooling demand is relatively small (11%).
- **Influence of occupancy on the effects of space layouts on BEP:** With the increase of occupancy, the reductions in heating and cooling demands decrease apparently. The values of the heating and cooling demands are almost the same in different layouts when layouts are highly occupied (12 occupants). This is because when most rooms are highly occupied, the interior partitions that enable different energy requirements in different rooms have less influence.

Table 4. Energy demand comparison between the layouts with same occupancy, adapted from [42].

Space Layouts	Heating Demand in Peak Winter	Lighting Demand in Peak Winter	Cooling Demand in Peak Summer	Lighting Demand in Peak Summer
a) space layouts with 4 occupants (kWh/day)				
Hive	4	14	14	3
Combi	5	10.5	13	1
Cell	7	8.5	13	1
Reduction (%)	**43%**	**39%**	**7%**	**67%**
b) space layouts with 6 occupants (kWh/day)				
Den 1	3	14	19	4
Den 2	7	8	17	2
Club	6	12	18	3
Combi	4	12	18	2
Cell	6	10	19	3
Reduction (%)	**57%**	**43%**	**11%**	**50%**
c) space layouts with 8 occupants (kWh/day)				
Hive	3	15	23	3
Combi	3	14	25	2
Cell	3	15	25	4
Reduction (%)	**0%**	**7%**	**8%**	**50%**
d) space layouts with 12 occupants (kWh/day)				
Hive	3	15	32	3
Den	3	15	33	3
Club	3	15	34	2
Reduction (%)	**0%**	**0%**	**6%**	**33%**
Biggest reduction	**57%**	**43%**	**11%**	**67%**

3.3. Methodologies Used in Previous Studies

Following the same procedure shown in Section 3.2, the other nine articles were reviewed and the information is shown in Table 2. The methodologies for studying the effects of space layouts on BEP used in the 10 articles are analysed and compared in this section, in terms of design variables, energy indicators and BEP calculation methods.

3.3.1. Design Variables

The following design variables of space layouts were used in these articles: function allocation and interior partition. Nevertheless, in most studies, they were mixed with other parameters. It is difficult to identify the isolated effects of space layouts. For instance, occupancy and distribution of workstations, and lighting and ventilation requirements were also changed in [42,63]. Other parameters were also changed, such as WWRs in [33,65,67–69,71], types and sizes of shading systems in [69] and opening states of windows in [63].

3.3.2. Energy Indicators

Regarding end uses of energy, most of these articles only simulated the energy use for space heating and space cooling, and half of the studies also included the energy use for lighting [33,42,65,67,71]. The energy use for ventilation has not been included yet, while one study tested the air volume supplied by natural ventilation [63]. In addition to energy use, some studies also calculated the indicators for thermal and visual comfort. These indicators include predicted mean vote (PMV) in [68], daylight autonomy in [67] and daylight illuminance in [68], which can provide extra information about BEP in addition to energy use. Regarding the system boundary of assessment, most of these articles defined their energy indicators unclearly: three articles described the system efficiency [33,65,71], and we assume that they tested the final energy; the others did not show system information, thus, we assume that they tested energy demands. Regarding the calculation period, most studies calculated the energy use for the whole year [33,64,65,68,70,71], and some studies only calculated it for peak days [42,63] or season representative days [67].

3.3.3. BEP Calculation Methods

Regarding BEP calculation methods, most studies used the dynamic simulation method for higher accuracy, except for two studies [33,71]. Lightscape in [42], Ecotect in [68] and IDA ICE 3.0 in [65] were used for daylighting simulation. TAS in [42], EnergyPlus in [64,67,69] and IDA ICE 3.0 in [65] were used for energy simulation. Although different calculation methods and simulation software were used in different articles, it is impossible to compare the accuracy of the calculation methods and simulation software between articles, as the calculation conditions in different articles are different in terms of materials, climates, WWRs, layouts (floor areas, interior partitions and functions), etc. Regarding the integration of multi-domains, two studies of [42,63] integrated daylighting and natural ventilation with energy simulation, using Excel to exchange data between the simulation tools of Lightscape and TAS. Another two studies of [33,71] considered the effect of daylighting on the reduction of the artificial lighting demand.

4. Effects of Space Layouts on Energy Use

Following the same procedure shown in Section 3.2, the other articles were reviewed. Their results were used for the analysis in Sections 4 and 5. As most information has already been shown in Table 2, the articles that were analysed in this section and Section 5 are introduced briefly. Some articles are not used for the analysis in Section 4 and also in Section 5: the studies of [33,71] did not show the results of energy performance, and the study of [70] did not present sufficient information for the on BEP calculation. As the articles in Table 2 mixed the design variables of space layouts with other parameters, the effects of space layouts cannot be identified directly from the results of these articles. Thus, we selected the cases that were usable to exclude the other design parameters, and reorganised their results to identify the isolated effects of space layouts. The effects on energy use are classified into the effects on space heating and cooling, lighting and ventilation as follows.

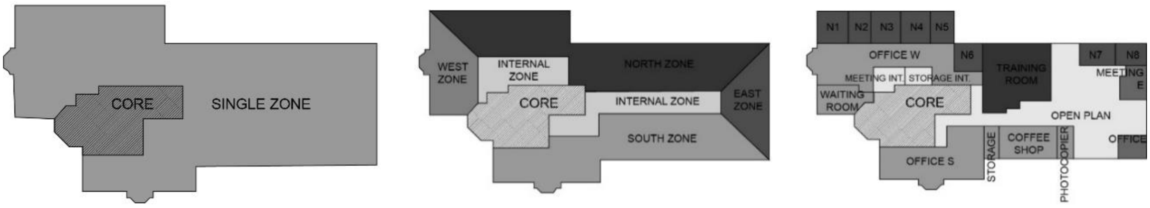
4.1. Effects on the Energy Use for Space Heating and Cooling

Most articles shown in Table 2 assessed the energy use for space heating and cooling. Yi [68] also tested the energy demands for heating and cooling, but in the results, heating and cooling demands were summed up as the annual energy use intensity, which cannot be used for detailed analysis in this study, thus, it was not included in this section. The studies of [42,64,65,67] were analysed and compared below.

4.1.1. Analysis of the Relevant Articles

Souza and Alsaadani [64] tested three layouts for an office building in London of the UK, in Cfb, and modelled them with different thermal zoning strategies (Figure 4). Detailed information about this article is shown in Table 2. Although this study focused on testing the effect of different thermal zoning strategies, the different zoning models actually represent different layouts. Ventilation rates and internal gains were also changed in some simulations, but we only selected the simulations in which only space layouts were changed. The selected results are shown in Table 5, and the reduction in the annual heating demand between different zoning strategies is 52%, while the value in the annual cooling demand is 24%.

Poirazis et al. [65] compared cell and open office layouts in Gothenburg of Sweden, in the humid continental climate (Dfb) as shown in Figure 5, and tested their final energy for space heating, space cooling and lighting. Detailed information about this article is shown in Table 2. In total, 102 simulations were run, and plenty of parameters were changed. We selected the layouts with same WWRs, although they still have different occupancy, lighting power densities, illuminance requirements, equipment power densities and heating, ventilation and air conditioning systems. Although the occupancy is different between the cell and open layouts, this case represents the real situation in practice. The final energy reductions between open and cell layouts are shown in Table 6. The reduction in the final energy for heating between the cell and open layouts is 14%, and the value for cooling is 57%. As shown in Table 6, with the increase of WWRs, the effects of space layouts on the final energy for heating, cooling and lighting decrease, which means that space layouts matter less when there are large windows.

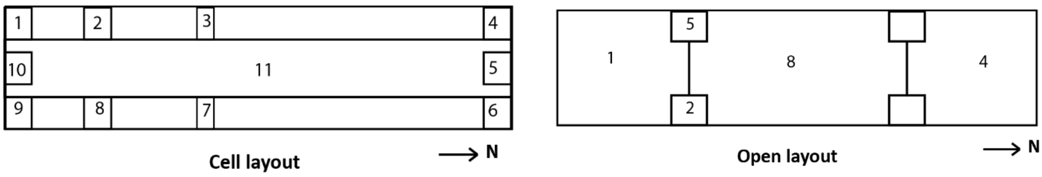


(**a**) single zone (**b**)5 zone (**c**) Office in use

Figure 4. Three layouts modelled with different thermal zoning strategies in [64]. The interior partitions divide the layout into different thermal zones.

Table 5. Annual energy demand comparison between three layouts, adapted from [64].

	Heating Demand	**Cooling Demand**
'Single zone' layout	8.47 (kWh/m^2)	28.04 (kWh/m^2)
'5-zone' layout	5.59 (kWh/m^2)	37.06 (kWh/m^2)
'Office in use' layout	11.69 (kWh/m^2)	29.72 (kWh/m^2)
reduction (%)	**52%**	**24%**



(**a**) 1,4,6,9: corner office; 2,8: double office; 3,7: single office; 5,10: meeting room; 11: cell;

(**b**) 1,4: corner zone; 8: intermediate zone; 2,5: meeting rooms;

Figure 5. Cell and open layouts in [65]. The interior partitions divide the layout into different thermal zones.

Table 6. Annual final energy comparison between cell and open layouts, adapted from [65].

	Reduction in Final Energy for Heating (Cell > Open)	**Reduction in Final Energy for Cooling (Cell < Open)**	**Reduction in Final Energy for Lighting (Cell < Open)**
30% WWR	14%	57%	4 kWh/m^2
60% WWR	11%	28%	4.1 kWh/m^2
100% WWR	11%	20%	2.7 kWh/m^2

Note: only the reductions and differences in kWh/m^2 were shown in the original paper.

Dino and Ucoluk [67] simulated the energy demands of a library building in Ankara of Turkey, in a cold semi-arid climate (BSk), with changed space layouts as well as building geometry. Detailed information about this article is shown in Table 2. Each layout has several functions, including reading, book storage, administration, café, working and conference, which vary in occupancy densities and equipment gains, heating and cooling set-points and illuminance set-points. The tested indicators relevant to energy use include heating, cooling and lighting demands. They were tested for 4 days, representing four seasons. As this study changed WWRs in addition to space layouts, we cannot identify the isolated effects of space layouts. Only the results of several layouts were shown in the original paper. We selected four layouts with the same geometry for comparison (Figure 6), which have a similar amount of total energy demand. The resulting energy indicators of the selected layouts are shown and compared in Table 7. According the table, with the change of space layouts and WWRs, the reductions are 19% for heating demand per day and 20% for cooling demand per day. Although with different WWRs, the total energy demands of different layouts are similar (around 3500 kWh/day). This implies that space layouts affect energy demands, although the isolated effects cannot be identified.

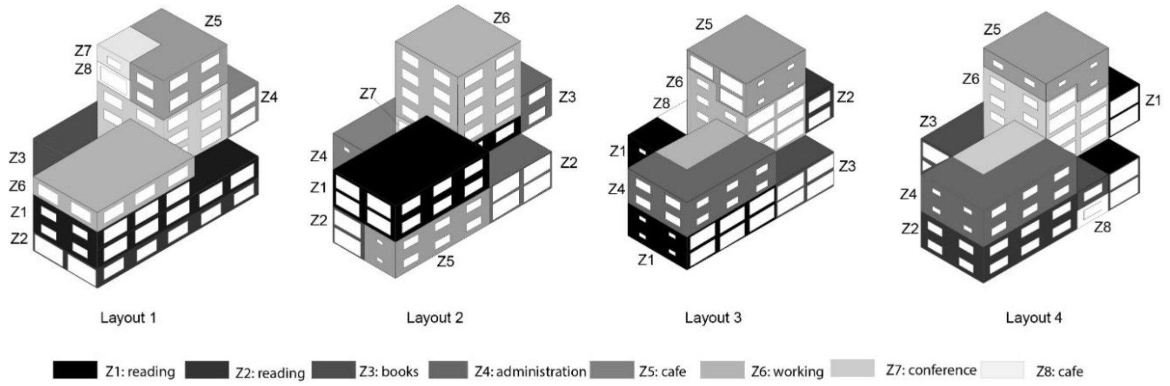


Figure 6. Four different layouts with the same geometry in [67]. Different colours represent different thermal zones.

Table 7. Energy demand comparison between the selected four layouts, adapted from [67].

	Heating Demand (kWh/Day)	Cooling Demand (kWh/Day)	Lighting Demand (kWh/Day)	Illuminance Set-Point Satisfaction
layout 1	1013	1154	1343	2285
layout 2	1092	978	1429	1949
layout 3	1249	924	1334	2378
layout 4	1159	1029	1286	2680
reduction (%)	**19%**	**20%**	**10%**	**27%**

4.1.2. Resulted Effects and Comparison

In addition to the results obtained from Section 4.1.1, the results obtained from the analysis of the example article shown in Section 3.2 are also used for the analysis in this section. The isolated effects of space layouts can be identified from these articles, except for [67]. By changing space layouts, the resulting reductions in the annual heating and cooling demands are up to 52% and 24%, respectively, for the case of an office building in the UK [64]. The resulting reductions in the heating and cooling demands in peak days are up to 57% and 11%, respectively, for the case of an office building in the UK [42]. The resulting reductions in the annual final energy for heating and cooling are up to 14% and 57%, respectively, for the case of an office building in Sweden [65]. The influence of occupancy on the effect of space layouts on BEP can be identified from [42] as well as the influence of WWRs [65], which show that with the increase of occupancy and WWRs, the reductions between layouts in heating and cooling demands decrease apparently.

Regarding the assessment boundary, both energy demand [42,64] and final energy [65] were tested. Regarding the assessment period, one year [64,65], peak days in winter and summer [42] and four season days [67] were tested. Regarding the BEP calculation method, the thermal zone division would highly affect the accuracy of the results, as shown in [64]. A simulation model with the detailed thermal zone division as shown in Figure 4c is needed for future studies. In total, three climates (Cfb, Dfb, BSk) were tested and the isolated effects of space layouts were only identified for Cfb and Dfb.

However, their results cannot be compared as different layouts are used for the two climates, as well as different energy indicators: heating and cooling demand in peak day [42] and annual heating and cooling demand [64] for Cfb, and annual final energy for heating and cooling for Dfb [65]. Although the studies of [42,64] tested the same climates, the layouts used in the two articles are different in floor areas, interior partitions and functions, thus, their results also cannot be compared.

4.2. Effects on the Energy Use for Lighting

Three of the articles in Table 2, which are also analysed in Section 4.1, studied the effects of space layouts on the energy use for lighting [42,65,67]. The resulted effects on the energy use for lighting in the three articles are shown Tables 4, 6 and 7, respectively. As shown in Table 4, in the study of [42], the biggest reduction in the lighting demand of peak summer is 67%, although the value of the lighting demand is relatively small. The reduction in the lighting demand of peak winter is 43%. Moreover, with the increase of occupancy, the reductions between layouts in the lighting demands of both peak winter and peak summer decrease apparently. The lighting demands of different layouts are almost the same when the layouts are highly occupied with 12 occupants. In the study of [65], the reduction in the final energy for lighting cannot be identified from the original article as only the demand difference in kWh/m^2 is given. However, as shown in Table 6, the effect of space layouts on the lighting demand decreases with the increase of WWRs. From the study of [67], the isolated effect of space layouts on the lighting demand cannot be identified, as WWRs were also changed. Regarding the tested climates, three climates (Cfb, Dfb, BSk) were tested and the isolated effects of space layouts were only identified for Cfb and Dfb. However, their results cannot be compared, as different layouts were used for the two climates, as well as different energy indicators: lighting demand in peak days for Cfb [42] and annual final energy for lighting for Dfb [65]. Compared to the energy use for space heating and cooling, the articles on the energy use for lighting are much less.

4.3. Effects on the Energy Use for Ventilation

There is only one article that tested the ventilation performance among the articles shown in Table 2. In their another study, Musau and Steemers [63] tested the effect of space layouts on the ventilation performance for office buildings in Garston of the UK, in Cfb. The basic settings were the same as in [42]. Detailed information about this article is shown in Table 2. One indicator relevant to ventilation was calculated, i.e., fresh air volume (m^3) supplied by natural ventilation through background vents, which was tested for the peak winter and summer. The results of the original paper were reorganised to identify the effect of space layouts in Table 8. According to this table, the biggest reduction between layouts in the air volume supplied by vents of peak winter is 65%. By comparing the variants with a different occupancy in Table 8, the following conclusion can also be drawn: the higher the occupancy is, the lower the effect of space layouts on the air volume supplied by natural ventilation in peak winter. Only one climate was tested, i.e., Cfb, and the isolated effect of space layouts was identified for this climate. More studies are needed for this topic specifically for the energy use for ventilation.

Table 8. Comparison of the fresh air volume supplied by natural ventilation, adapted from [63].

Air Volume Supplied by Vents of Peak Winter with Closed Window (m^3)				
	8 occupants	6 occupants	4 occupants	2 occupants
Cell	310	250	170	80
Comb	320	250	170	80
Club	580	490	380	200
Den	620	620	460	230
Hive	620	620	460	230
Reduction (%)	**50%**	**60%**	**63%**	**65%**
Biggest reduction (%)		**65%**		

5. Effects of Space Layouts on Occupant Comfort

In addition to energy use, the articles in Table 2 also tested the indicators for occupant comfort. Among the articles shown in Table 2, only thermal and visual comfort was tested, and the articles relevant to occupant comfort were analysed in detail and compared below.

5.1. Effects on Thermal Comfort

There are two articles that test the effects of space layouts on thermal comfort [68,69], and they were analysed in detail and compared below.

5.1.1. Analysis of the Articles Relevant to Thermal Comfort

Yi [68] simulated an office building in Seoul of South Korea, in the humid continental climate (Dwa), with changed space layouts as well as WWRs. Detailed information about this article is shown in Table 2. We only selected three layouts for comparison (Figure 7), as their WWRs varied from 31.4% to 35%, which is a small variation. The tested indicators relevant to thermal comfort is PMV. The results are reorganised in Table 9, which shows that the reduction in PMV is 13%. The reduction is mainly caused by changing space layouts, as the WWRs have a much smaller variation.

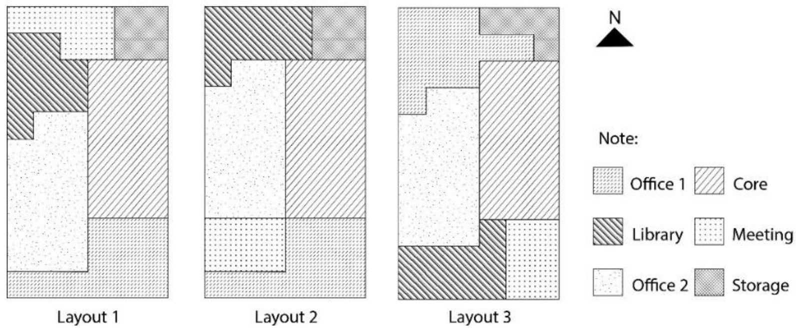


Figure 7. Three layouts with similar WWRs in [68]. The interior partitions divide the layout into different thermal zones.

Table 9. Energy performance comparison between the selected layouts, adapted from [68].

	PMV	Indoor Daylight Level (Lux)	Shading Level
Layout 1	−1.60	309.30	90.80
Layout 2	−1.79	348.50	89.20
Layout 3	−1.55	335.70	89.26
Reduction (%)	**13%**	**11%**	**2%**

Rodrigues et al. [69] simulated a residential building in Coimbra of Portugal, in a temperate Mediterranean climate (Csb), with changed space layouts, WWRs, window orientations, shading systems and floor areas. Detailed information about this article is shown in Table 2. The tested indicator is thermal discomfort penalty (°C), which was calculated by multiplying a weight factor with the difference between the calculated hourly interior air temperature and the temperature limit for thermal comfort. Two layout sets were compared: one has one floor and the other one has two floors (Figure 8). The results of the two sets of layouts are shown and compared in Table 10. The biggest reduction in the thermal discomfort is 33% between one-floor layouts and 29% between two-floor layouts. The isolated effect of space layouts on thermal comfort cannot be identified from this study, while it shows the effect of space layouts combined with other parameters, i.e., WWRs, window orientations, shading systems and floor areas.

Table 10. Hourly thermal discomfort comparison between layouts, adapted from [69] (TDP: thermal discomfort penalty. The higher the thermal penalty, the worse the thermal performance).

Layouts with One Floor												
TDP of layouts with one floor	**layout-1 20.5 °C**	**layout-2 23.0 °C**	**layout-3 23.3 °C**	**layout-4 25.3 °C**	**layout-5 25.7 °C**	**layout-6 25.8 °C**	**layout-7 26.4 °C**	**layout-8 26.6 °C**	**layout-9 27.4 °C**	**layout-10 27.9 °C**	**layout-11 29.6 °C**	**layout-12 30.5 °C**
reduction	33%											
layouts with two floors												
TDP of layouts with one floor	**layout-13 21.5 °C**	**layout-14 22.8 °C**	**layout-15 22.8 °C**	**layout-16 23.0 °C**	**layout-17 23.6 °C**	**layout-18 25.2 °C**	**layout-19 25.2 °C**	**layout-20 25.7 °C**	**layout-21 25.8 °C**	**layout-22 28.6 °C**	**layout-23 28.9 °C**	**layout-24 30.2 °C**
reduction	29%											

1st floor 2nd floor

(a) Layout example with one floor (b) Layout example with two floors

Figure 8. Examples of two layout sets in [69] (left: layout with one floor, right: layout with two floors). The interior partitions divide the layout into different thermal zones.

5.1.2. Resulted Effects and Comparison

The isolated effects of space layouts cannot be identified in the two studies [68,69], as both studies also changed other parameters, i.e., WWRs in [68], and WWRs, window orientations, shading systems and floor areas in [69]. However, as the variation of WWRs in [68] was small, the reduction in thermal discomfort is mainly caused by changing space layouts. Thus, the reduction in PMV is around 13% by changing the space layouts in South Korea [68]. Two climates were tested (Dwa and Csb), but the isolated effects of space layouts were only identified for Dwa.

5.2. Effects on Visual Comfort

There were two studies that tested the effect of space layouts on visual comfort [67,68]. In the study of Yi [68], the indoor daylight level (illuminance) and shading level (the ratio of shaded floor area at 12 pm, 21th Dec) were tested, in addition to PMV. The resulting reduction was 11% in indoor daylight level and 2% in shading level, as shown in Table 9. The study of Dino and Ucoluk [67], in addition to energy use, tested the illuminance set-point satisfaction, which refers to how close the calculated daylight illuminance is to the user-defined illuminance set-point. The resulting reduction in the illuminance set-point satisfaction is 27%, as shown in Table 7. In both studies, WWRs were also changed in addition to space layouts. However, the variation of WWRs in [68] was small; thus, the reduction is mainly caused by changing space layouts. Two climates were tested (Dwa and BSk), but the isolated effects of space layouts were only identified for Dwa.

6. Conclusions and Recommendations

In this paper, the articles relevant to the effects of space layouts on building energy performance (BEP) were reviewed. A methodology for studying the effects of space layouts on BEP is proposed in Section 3.1, regarding design variables, energy indicators and BEP calculation methods. Among the large number of studies on building energy-efficient design, only 10 articles were found relevant to the specific topic and they were reviewed in detail to identify the isolated effects of space layouts. The review results show that by only changing space layouts, the energy use for space heating, space cooling and lighting can be reduced significantly.

The resulting effects can be categorised into the isolated effects of space layouts on BEP, and the influence of other design parameters on the effects of space layouts on BEP. Moreover, the recommendations were added regarding future research direction, as well as the methodology for studying the effects of space layouts.

6.1. Isolated Effects of Space Layouts on BEP

The isolated effects of space layouts on BEP tested in the 10 articles were classified into the effects on energy use and the effects on occupant comfort. The effects of space layouts on the energy use for space heating and cooling, lighting and ventilation are as follows:

- **Energy use for space heating and cooling**: The isolated effects were identified, and both energy demand and final energy for one year were tested. The resulting reductions in the annual heating and cooling demands were substantial, and the reductions were up to 52% and 24%, respectively, for the case of an office building in the UK with varied thermal zoning. The resulting reductions in the heating and cooling demands in peak days were up to 57% and 11%, respectively, for the case of an office building in the UK. The resulting reductions in the annual final energy for heating and cooling are up to 14% and 57%, respectively, for the case of an office building in Sweden.
- **Energy use for lighting**: Only the isolated effects on the lighting demand for peak summer and winter were tested, and the resulting reductions were significant. The reductions were up to 67% and 43%, respectively, for the case of an office building in the UK.
- **Energy use for ventilation**: Only the air volume supplied by natural ventilation was tested for the peak winter; the resulting reduction was significant, namely, up to 65% for the case of an office building in the UK.

The effects of space layouts on the thermal and visual comfort were as follows:

- **Thermal comfort**: PMV and the thermal discomfort (difference between air temperature and thermal comfort temperature) were tested. Although the isolated effects cannot be identified, the approximate effect on PMV can be identified, and the resulting reduction was smaller than the ones in energy use; around 13% for the case of an office building in South Korea.
- **Visual comfort**: Similar to the thermal comfort, only the approximate effect on the illuminance and shading level can be identified, and the resulting reductions are smaller than the ones in energy use; are around 11% and 2%, respectively, for the case of an office building in South Korea.

6.2. The Influence of Other Parameters

From the results of the 10 articles, the influence of other design parameters, i.e., occupancy and WWRs, on the effects of space layouts on BEP can also be identified, as follows:

- **Influence of occupancy**: With the increase of occupancy, the effects of space layouts on the heating demand, cooling demand, lighting demand and air volume from natural ventilation decrease.
- **Influence of WWRs**: With the increase of WWRs, the effects of space layouts on the heating demand, cooling demand and lighting demand decrease.

Regarding climates, in total, five climates were tested for the effects of space layouts on BEP. Two climates were tested for the isolated effects on the energy use for space heating and cooling, and two climates were tested for the isolated effects on the energy use for lighting. However, the results for space heating, cooling and lighting cannot be compared between the climates, as different energy indicators and layouts were used for these climates. Moreover, only one climate was tested for the isolated effects on the energy use for ventilation, thermal comfort and visual comfort, respectively. In addition, the construction site and the surrounding buildings were not considered in the 10 articles analysed in this paper, and these would highly influence the effect of space layouts on BEP.

6.3. Recommendations

Designers and architects should consider BEP while designing space layouts, as the effects of space layouts on BEP are significant, although the effects have not been fully confirmed. Studies are needed to compare the effects of space layouts between different climates regarding different energy indicators, in order to obtain the influence of climates on the effects of space layouts on BEP. In order to compare the results between different climates, the same layout should be used in each climate with the same conditions, such as interior partitions, dimensions, forms, orientations and functions, while the functional requirements (such as heating and cooling set-points) and envelope design (transmittance, window area) should adapt to the local standards in order to be suitable for practice and the local climate. Moreover, it would be interesting to test the effects of space layouts on BEP considering the influence of the context with surrounding buildings.

More studies are needed to fully explore the effects of space layouts on BEP. The recommendations for future studies regarding the methodology for studying the effects of space layouts on BEP are as follows.

- **Design variables:** A systematic study on the effects of space layouts on BEP should first only change the design variables of space layouts, while keeping other design parameters constant, in order to identify the isolated effects of space layouts. Then, by adding other design parameters one by one, their influence on the effects of space layouts can be obtained.
- **Energy indicators:** Regarding energy use, more studies are needed, especially on the energy use for lighting and ventilation for a long assessment period, such as one year. Regarding occupant comfort, more indicators for thermal and visual comfort need to be tested.
- **BEP calculation methods:** Regarding the BEP calculation method, a calculation tool with high accuracy is needed. The integration of multi-domain simulations is necessary to predict the real situation and better represent the effects of space layouts, such as integrating daylighting simulation and natural ventilation simulation with energy simulation. In addition, a detailed thermal zone division regarding the different requirements of spaces is necessary as shown in Figure 4c, as it highly affects the results.

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