4 Indoor thermal comfort in different building blocks

The previous chapters reviewed the environmental impacts of courtyards and common thermal comfort standards. This chapter begins Part B which discusses indoor thermal comfort in different housing blocks including low-rise residential courtyard buildings.

The main aim is to explore and answer to the question that whether courtyards can provide more indoor comfort and energy efficiency as compared to other building types. The results will determine if this study should go further with courtyard buildings or with other building forms. This chapter discusses a parametric study done by computer simulations for the climate of the Netherlands.

Energy use impact of and thermal comfort in different urban block types in the Netherlands[1]

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Abstract

This paper discusses the energy and comfort impact of three types of urban block configuration in the Netherlands. The annual heating and lighting energy demand, and summer thermal comfort hours are compared. In total, 102 thermal zones forming single, linear and courtyard building combinations are simulated within the Netherlands' temperate climate. The results demonstrate the importance of the surface-to-volume ratio in achieving both annual energy efficiency and summer thermal comfort. Considering different types with 1-, 2- and 3-storey heights, the courtyard model has the lowest energy demand for heating and the highest number of summer thermal comfort hours.

Keywords

Energy use, thermal comfort, urban block types.

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§ 4.1 Introduction

The idea of using the environmentally best building shape was addressed in the 1960s by architects [1] and urban planners [2]. In the beginning, urban designers and planners considered the most favourable land use, whereas architects studied the forces of nature that shape our buildings. Ever since, with increasing environmental concerns and diminishing fossil fuels, more intense attention has been directed to the effect of urban morphology [3-9] and building form [10-12] on energy consumption within the built environment. In this regard, urban designers generally concentrated on the outdoor environment and architects and building physicists on the indoor environment.

On this account, architects' and urban designers' responsibilities overlap at the scale of the urban block, potentially causing design conflicts. For instance Olgyay [1], as a building physicist, states "all shapes elongated on the north-south axis work both in winter and summer with less efficiency than the square one. The optimum lies in every case (climate) in a form elongated somewhere along the east-west direction". However, many studies from urban designers as Yezioro [13] show: "rectangular urban squares elongated along the north–south direction are the best solution (for solar gains)". Therefore, this chapter tries to investigate the effect of different urban block layouts (urban designers' decision) on indoor environment (building physicists' objective).

There is a body of literature dealing with urban block layout effects on the indoor environment. Regarding different layouts, Steemer et al. [7] proposed six archetypal generic urban forms for London (51°N) (Figure 1) and compared incident solar radiation, built potential and day-lighting criteria. They concluded that the courtyard performs best among these six archetypes. Ratti et al. [14] conducted similar analyses for the hot climate city of Marrakech (31°N). Okeil [15] generated a built form named the Residential Solar Block (RSB), which later was compared with a slab and a pavilion court [16]. The RSB was found to lead to an energy efficient neighbourhood layout for a hot and humid climate at a latitude of 25°N. Furthermore, Thapar and Yannas [17] showed the importance of ventilation in urban squares for the hot and humid climate of Dubai. They also indicated the role of vegetation in providing a comfortable microclimate. Yang, Li [18] studied four parameters in Beijing's climate which influence the urban block thermal environment: block height, thermal mass, material conductivity and surface albedo. They found the geometry (height) of the square is the most important, and the surface albedo the least one. Moreover, Taleghani et al. [19] indicated that a single-family house with no open space is more energy efficient than a courtyard, an atrium and a building with a sunspace in Rotterdam (52°N). The explanation related to the surface-to-volume ratio of dwellings. This chapter continues this work on an urban building scale. In addition, since solar radiation plays an important role in heat gains, each urban block form in all of these studies is optimised for a specific latitude.

In this chapter, the categories of Steemers et al. [7] shown in Figure 1 is simplified to three urban layouts. These urban layouts shape almost all urban layouts; single shape like villa and free standing buildings, linear shape like all urban canyons and streets, and finally courtyard form which is visible in all urban blocks and plazas.

The heating and lighting energy demand and thermal comfort of dwellings in these urban forms were studied for the climate of Rotterdam in the Netherlands. One hundred and two simulations were run to estimate the heating and lighting energy demand of zones within the three different urban forms, in one, two and three storey configurations. Afterwards, calculations with different algorithms were done to estimate the thermal comfort in each. Finally, the results were interpreted based on the following indices: surface-to-volume ratio (the level of zone exposure to its outdoor environment), solar gains (the effect of the sun), heat loss through external air (the effect of wind), and daylight factor (the potential of zones to benefit from natural lighting).

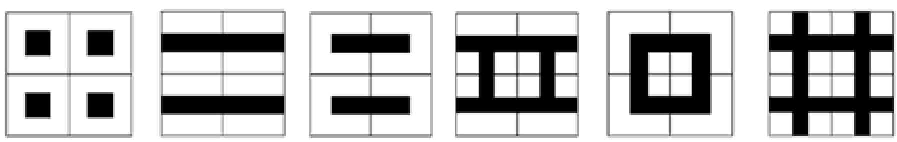

Figure 1
Generic urban forms. From left to right: pavilions, slabs, terraces, terrace-courts, pavilion-courts and courts [14].

§ 4.2 Method and models

For this building simulation research the DesignBuilder software was used, which is based on the state-of-the-art building performance simulation engine, EnergyPlus. The simulation principle used by DesignBuilder is one of the most comprehensive methods with dynamic parameters and it includes comprehensive accounting of energy inputs and energy losses. The simulation is based on EnergyPlus hourly weather data of the Netherlands, taking into account solar heat gains through windows, heat conduction and convection between different zones and the energy applied or extracted by mechanical systems [20, 21], among other things. Moreover, DesignBuilder is validated through the BESTest (Building Energy Simulation TEST) technique, developed under auspices of the International Energy Agency. For this study, the following was implemented in DesignBuilder:

Construction

In the simulations, the wall, roof and glazing types were parameterised with the data in Table 1.

Section	U-value W/(m²K)	Rc-value (m²K)/W
Wall: Brickwork Outer Leaf (100mm) Air Gap (40mm) EPS Expanded Polystyrene (100mm) Concrete Block (100mm) Gypsum Plastering (10mm)	0.31	3.0
Roof: Bituminous roof finish (2mm) Fibreboard (13mm) XPS Extruded Polystyrene (80mm) Cast Concrete (100mm) Gypsum Plastering (15mm)	0.33	2.9
Glazing: Generic PYR B Clear (6mm) Air (6mm) Generic Clear (6mm)	2.55	0.39

Table 1
The wall, roof and glazing properties used in the simulations and calculations.

HVAC

The heating system considered for models is based on radiator (same as actual Dutch low-rise dwellings). It is assumed that radiators turn on with the heating set point of 21° Celsius (and the heating set-back is 12°C). Generally, radiators are based on electricity and hot water. For the simulations, radiators work with hot water supplied by a gas boiler. Moreover, the radiant fraction assumed is 0.65. Radiant fraction determines what fraction of the power input to the radiator is actually transferred to the space as radiant heat.

Regarding the ventilation, it is assumed to use natural ventilation by opened windows (15%) when the indoor air temperature has risen to above 22°C. The models are not equipped with a cooling system since the predominant parts of Dutch dwellings are in free running mode during summer. Furthermore, there is an operation schedule for the zones. The operation schedule specifies the times when full setback and set points should be met. In this regard, the zones are assumed to be occupied between 16:00 and 23:00.

Glazing type and lighting

Most of Dutch dwellings have large glazing to achieve maximum daylight. This is mostly because of the high latitude (52°N) and consequently low sun angle during the winter time (15° at 12:00 on 21st of Dec). The amount of 30% window to wall ratio is a very close average used for modelling in the Netherlands. The external window type for the models is a double glazed (Dbl LoE) with an air gap in between layers (U- value= 2.55 W/m^{2}K). Figure 2 shows the input data used for the lighting simulations. Based on the weather data, there were 45 days completely sunless and 76 gloomy days.

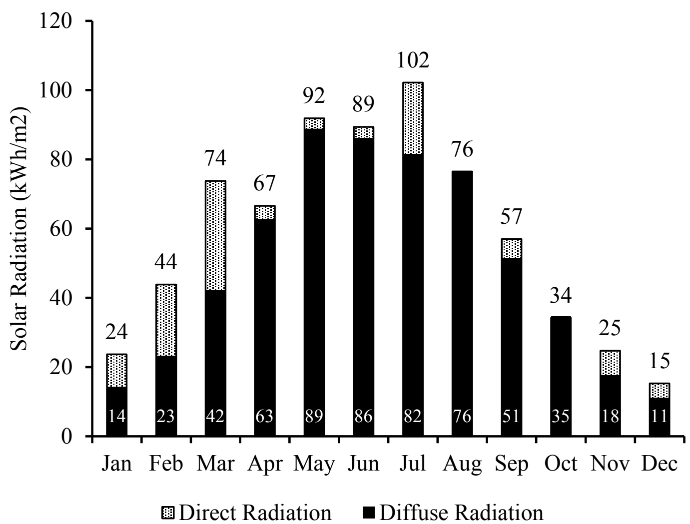

Figure 2
Monthly average global radiation levels in Rotterdam, split into diffuse radiation and direct radiation.

For lighting calculations, Designbuilder v.3 uses Radiance daylight simulation engine. Inside the models, one sensor at the centre of each zone located in the working plane (0.8m above the floor) is assumed. DesignBuilder calculates illuminance levels at each time step (every hour) during the simulations. The daylight illuminance level in a zone depends on many factors, including sky condition, sun position, photocell sensor positions, location, size, and glass transmittance of windows and window shades. Calculation of energy demand for lighting depends on daylight illuminance level, illuminance set point, fraction of zone controlled and type of lighting control. In this project, the minimum required illuminance level is 150 lux. Moreover, suspended luminaire type with 0.42 radiation fraction is assumed (this is the fraction of heat from lights that goes into the zone as long wave radiation).

Climatic data

The climate of Rotterdam (52°N, 4°E) in the Netherlands is known as a temperate climate based on the climatic classification of Köppen-Geiger [22]. The prevailing wind of Rotterdam is South-West. The mean annual dry bulb temperature is 9.9 °C (Figures 3).

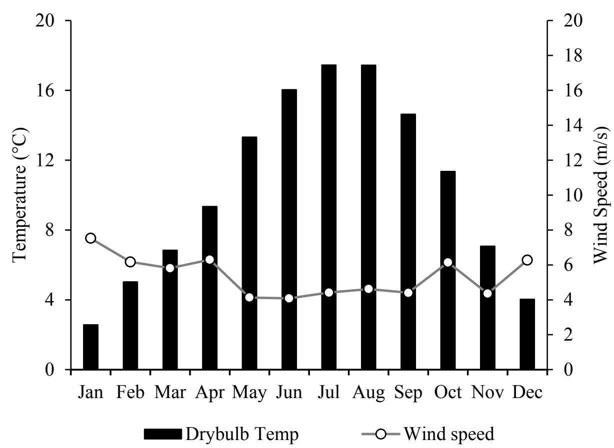

Figure 3
Mean dry bulb outdoor temperature and mean wind speed of Rotterdam as used in the calculations.

Zone shape and size

The dwellings modelled are based on square zone modules with a net size of 5 * 5 meter. A single zone with the mentioned dimensions is the first model. Two linear models containing 8 zones (2 * 4 zones) are the second model. The elongation of two lines is in east west direction. The distance between two lines is 5 meters. The third main model is a courtyard building involving 8 zones. A courtyard at the centre of a block of houses is also net 5 * 5 meter (Figure 4, above). Furthermore, the window to wall ratio is 30%. This chapter presents results in tabular format corresponding to their physical forms (Figure 4, below). Moreover, the surface to volume ratio of each model is described in Table 2. Below- The layout of the different building types: single zone, linear combination, and courtyard combination of zones.

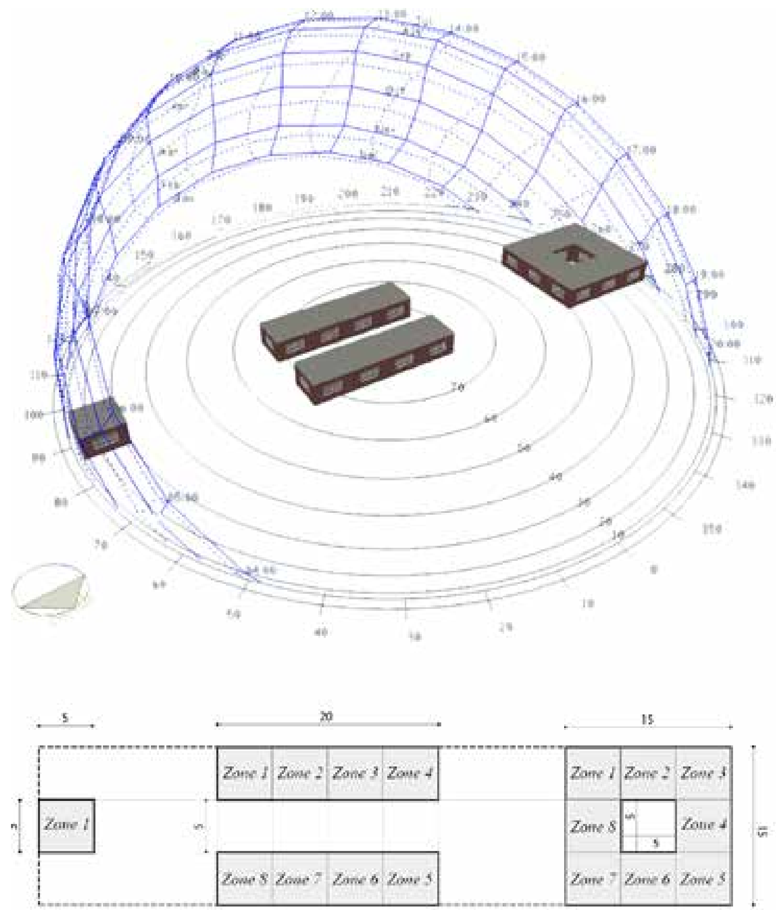

Figure 4
Mean dry bulb outdoor temperature and mean wind speed of Rotterdam as used in the calculations.

Model	Single	Linear	Courtyard
1 storey	1.47	1.16	0.87
2 storey	1.13	0.83	0.73
3 storey	1.02	0.72	0.62

Table 2
The surface to volume ratio of the different models (average values over all storeys).

§ 4.3 Thermal comfort in summer

Thermal comfort temperature boundaries reflect within which temperature range the indoor environment is assumed to be comfortable for users [23]. The conventional approach to analysing thermal comfort in simulation studies is to study the heat exchange between the human body and the environment. In the 1970s, Fanger [24] developed his well-known thermal comfort equation which subsequently was adopted by ISO [25]. However, more recently Humphreys and others stated that the application of steady state models led to an incorrect evaluation of thermal discomfort, typically overestimating it, because of insufficient acknowledgment of the human capacity for thermal adaptation [26-29]. Therefore, in this chapter the European thermal comfort standard [30] was used to estimate thermal comfort in the models. This standard is based on the Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission. In this project, 26 European buildings in France, Greece, Portugal, Sweden and the UK were surveyed covering free running, conditioned and mixed-mode buildings [31]. Based on the survey, different adaptive algorithms for each participating country were developed (Table 3).

Country	Adaptive control algorithm	
	Trm≤10°C	Trm>10°C
All	22.88°C	0.302 * Trm + 19.39
France	0.049 * Trm + 22.85	0.206 * Trm + 21.42
Greece	NA	0.205 * Trm + 21.69
Portugal	0.381 * Trm + 18.12	0.381 * Trm + 18.12
Sweden	0.051 * Trm + 22.83	0.051 * Trm + 22.83
UK	0.104 * Trm + 22.85	0.168 * Trm + 21.63

Table 3
Adaptive comfort algorithms for individual countries [29].

In 2007, the European Committee for Standardisation (CEN) released EN15251:2007 [28] with the equation:

$$T_{co} = 0.33 * T_{rm7} + 18.8°C \qquad (1)$$

Where

T_{co} (°C) is the comfort temperature and θ_{rm7} (°C) is the exponentially weighted running mean of the daily mean external air temperature (θ_{ed}), and is calculated from the formula:

$$\theta_{rm} = (1-\alpha) \times (\theta_{ed-1} + \alpha.\theta_{ed-2} + \alpha.\theta_{ed-3} + \ldots) \quad (2)$$

This equation can be simplified to:

$$\theta_{rm} = (1-\alpha) \times (\theta_{ed-1} + \alpha.\theta_{rm-1}) \quad (3)$$

Where

α is a reference constant value, ranging between 0 and 1, θ_{rm} = running mean temperature for today, θ_{rm-1} = running mean temperature for previous day, θ_{ed-1} = the daily mean external temperature for the previous day, θ_{ed-2} = the daily mean temperature for the day before, and so on.

Humphreys proposed 0.8 for α based on the average of five countries studied in SCATs project. Therefore, the following approximate formula can be used where records of daily mean external temperature are not available:

$$\theta_{rm7} = \frac{(\theta_{ed-1} + 0.8\theta_{ed-2} + 0.6\theta_{ed-3} + 0.5\theta_{ed-4} + 0.4\theta_{ed-5} + 0.3\theta_{ed-6} + 0.2\theta_{ed-7})}{3.8}$$

(4)

Furthermore, the extent of the deviation of the indoor operative temperature from the comfort temperature is divided into four categories (table 4). Category II is selected as it matches with the building types studied in this chapter.

Category	Explanation	Limit of deviation	Range of acceptability
I	High level of expectation for very sensitive and fragile users (hospitals, ...)	±2°C	90%
II	Normal expectation for new buildings	±3°C	80%
III	Moderate expectation (existing buildings)	±4°C	65%
IV	Values outside the criteria for the above categories (only in a limited period)	±>4°C	<65%

Table 4
Suggested applicability for the categories and their associated acceptable temperature ranges (table after [28]).

The second category covers approximately 80% of satisfaction for building occupants, which is shown in Figure 7 by the bold lines. Furthermore, based on the comfort algorithm and the range permitted for the second category, ±3°C, Figure 8 presents the acceptable indoor operative temperatures for the free running mode period in Rotterdam. The duration of the free running mode period was based on the old Dutch standard for determining the energy performance of residential buildings [30]. This standard states that the free running mode typically occurs from 1st of May till 30th of September in the Netherlands.

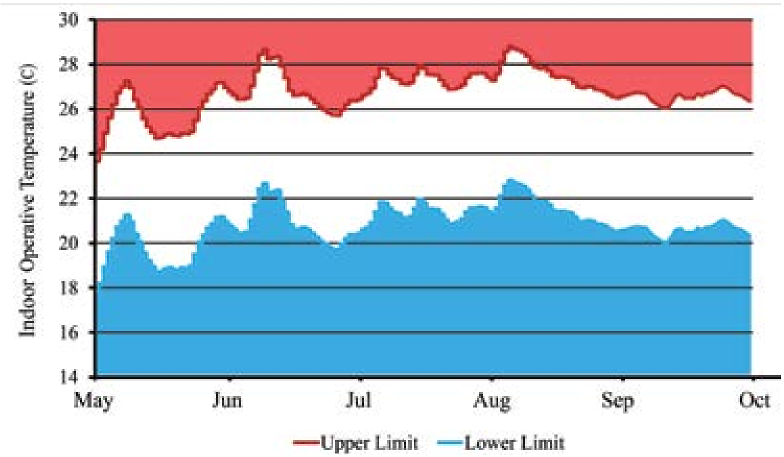

Figure 5
Comfort boundaries for a building in Rotterdam in free running mode during a whole year (based on category II from [30]).

§ 4.4 Results and discussion

§ 4.4.1 Energy consumption

As a first step, simulations were done for the three types of buildings: a single zone, two rows of four linear zones, and eight zones forming a courtyard. In the temperate climate of Rotterdam in winter, protection against wind and benefitting from the sun are very important. As can be seen in Figure 6, the prevailing wind of Rotterdam (south-west) influences the three zone combinations differently.

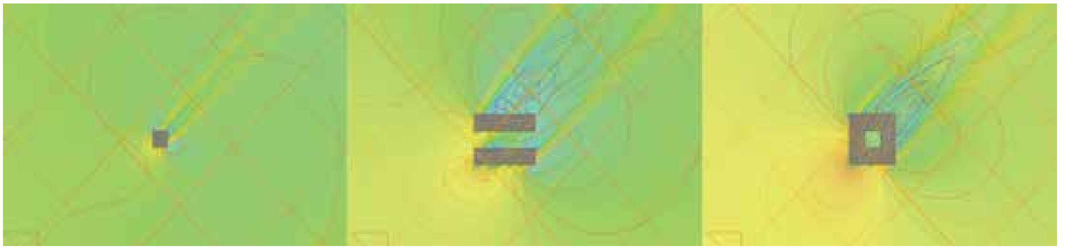

Figure 6
Wind flow pattern around the three building forms based on the mean wind speed of Rotterdam (5.5 m/s) in the free field (produced by DesignBuilder).

In addition, Figure 7 depicts a graphical overview of the daylight factor for the three zone combinations.

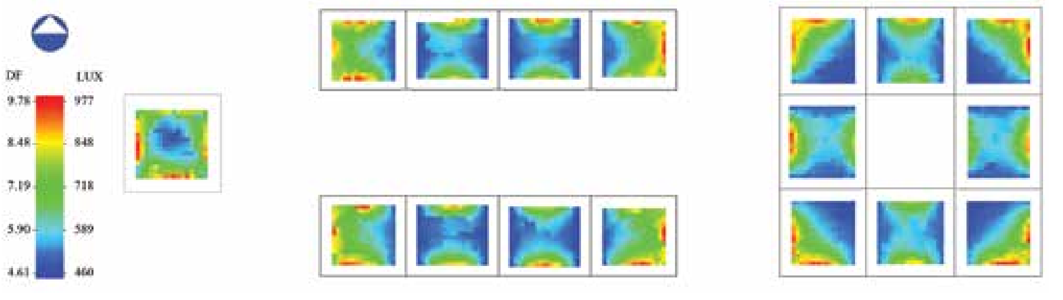

Figure 7
Daylight factor in the studied zones; the models are analysed with no blockage of sun, i.e. without any obstruction (produced by Radiance merged in DesignBuilder).

§ 4.4.1.1 One storey models

The results of the simulations are presented in Figure 8. These results are for one-storey zones which are 5 times 5 meters. Looking at the heat loss in the different zones and considering the prevailing wind, which comes from the south-west, it is logical that zones located in the south-west of the building have a greater heat loss through convection to external air. In this regard, the zones located on the eastern side are better protected and always have less heat loss (through convection to external air). Furthermore, solar heat gain through windows results from access to solar radiation. The more solar heat gain, the greater the chance to benefit from free heating (but also the higher the risk of overheating). Therefore, as seen in Figures 7 and 8b, zones located on the corners have a higher solar heat gain.

Likewise, the daylight factor is higher in the corner zones which have more access to the outdoor environment. In this regard, the single zone has four facades exposed to the outside; it also has the highest solar gain (139 kWh/m²) and daylight factor (6.8 %). The linear zone combination provides less exposed surfaces than the single zone. Therefore, the average solar gain is less: 82 kWh/m². This amount is even lower in the courtyard building, which has the smallest surface to volume ratio: 64 kWh/m². This amount is less than half of the potential of the single zone dwelling.

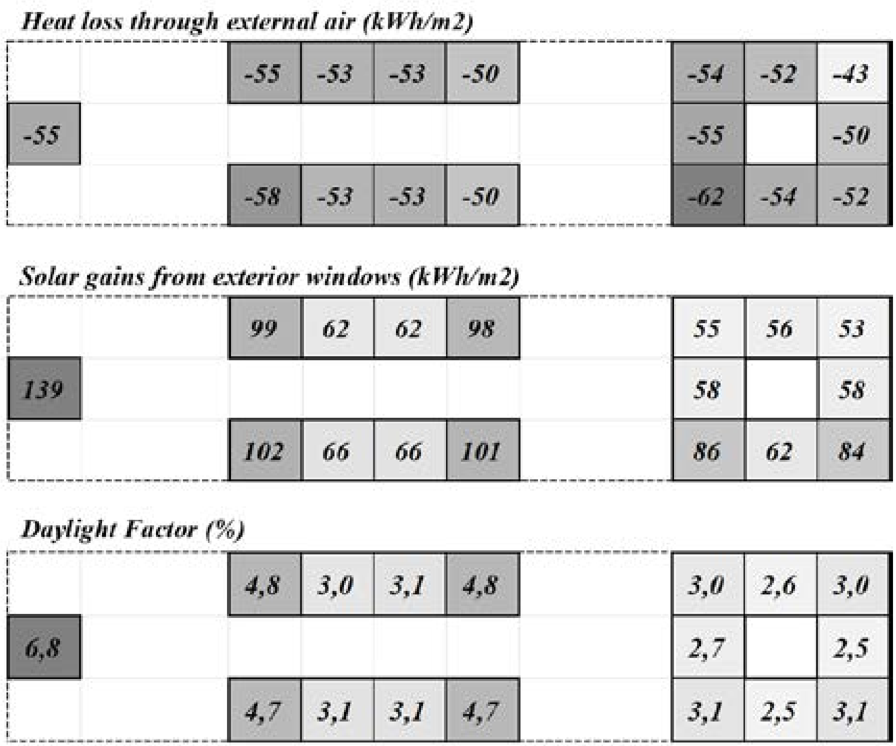

Figure 8
From top to bottom: a) heat loss by infiltration (kWh/m²), b) solar gain through exterior windows (kWh/m²), c) daylight factor (%) of the three zone combinations.

§ 4.4.1.2 Multi-storey models

By increasing the number of floors from 1 to 2 or 3, the energy gains and losses change in different ways in the simulated layouts. Based on Figure 9, the solar gain (and daylight factor) do not change much in the single zone model as a result of increasing the height. Conversely, this amount decreases in the linear and courtyard layouts. Considering the geometry of the models (Figure 10), the surface to volume ratio decreases when the number of storeys increases. Therefore, decreasing surface to volume ratio decreases direct solar gains. In other words, by increasing the number of floors, the sun will penetrate less into the linear and the courtyard shapes. Moreover, solar access to the lower storeys is more blocked by the zones at the northern side of the buildings when the number of storeys increases.

By increasing the height, the heat loss through external air also increases (on average over all floors). This happens because the wind speed is higher at higher altitudes. Here again, the differences depend on the surface to volume ratio. Since the single zone has the highest ratio among the models, the impact of wind is more clearly visible when the number of storeys increases from 1 to 3 (causes 19 kWh/m^2 of additional heat loss). The differences between the 1-storey and the 3-storey models are smaller for the linear and courtyard shape models (12 and 4 kWh/m^2 respectively).

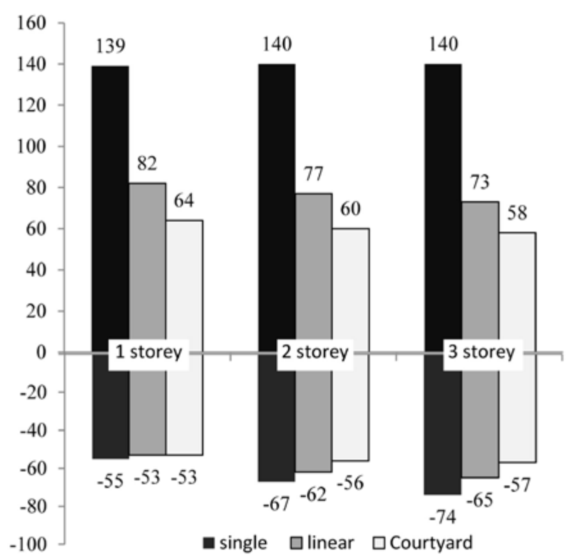

Figure 9
Ventilation heat loss and solar gains (average values of all the zones are included).

The average of the monthly heating and lighting energy demands of the multi-storey models is illustrated by Figure 11. Heating energy demand is practically zero May through September. These are the months in which the zones are in free running mode.

Considering the surface to volume ratios mentioned in Table 2, higher heating energy demand for the single zone model (Figure 11 left) is predictable during cold periods. Likewise, the linear shape models are exposed more to the outdoor conditions than the courtyard zone type models. Therefore, the differences between the heating demand of the models are amplified during more extreme weather (November through February). These differences are more significant in the 3-storey models. In this case, the single zone is highly exposed, and the courtyard is relatively protected from its outdoor environment.

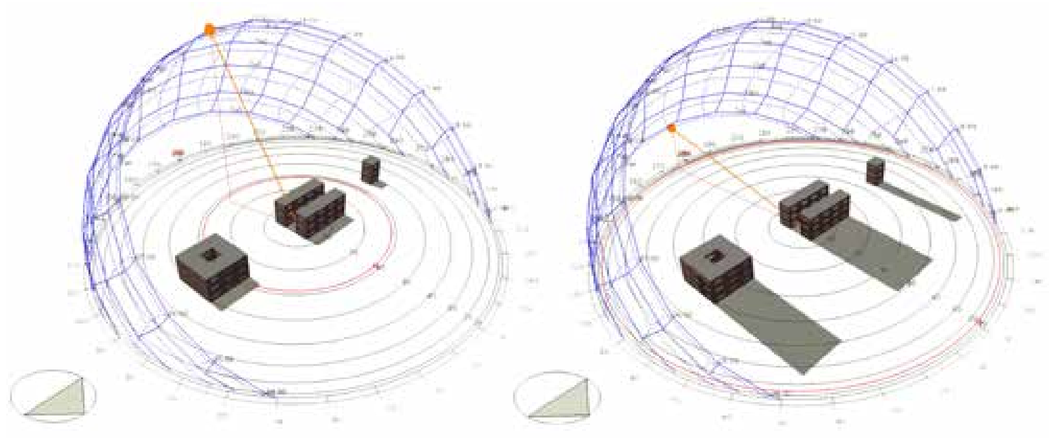

Figure 10
Solar access on 21st of Jun (left) and 21st of Dec (right) at 12:00 for the latitude of Rotterdam, 52° N (produced by DesignBuilder).

From the point of view of lighting, the energy demand is reversed. Based on Figures 7 and 8 (b, c) and Figure 9, the single zone building receives more solar heat gains and has the highest daylight factor among the other model types. Therefore, as can be seen in Figure 11 (right), it requires less energy for lighting. Also the linear shape models have lower energy demand for lighting since they are less shaded than the courtyard models. During summer, when there is direct sunlight (a solar angle of 61° at 12:00 h solar time on June 21st in Rotterdam, Figure 10 left), the differences between the models are smallest since most of the solar heat is gained through horizontal surfaces. However, on the 21st of December (Figure 10 right), when the solar angle is 15° at 12:00 h solar time, the surface to volume ratio and exposure of the facades of the models lead to higher energy consumption in the courtyard dwellings and in the linear dwellings.

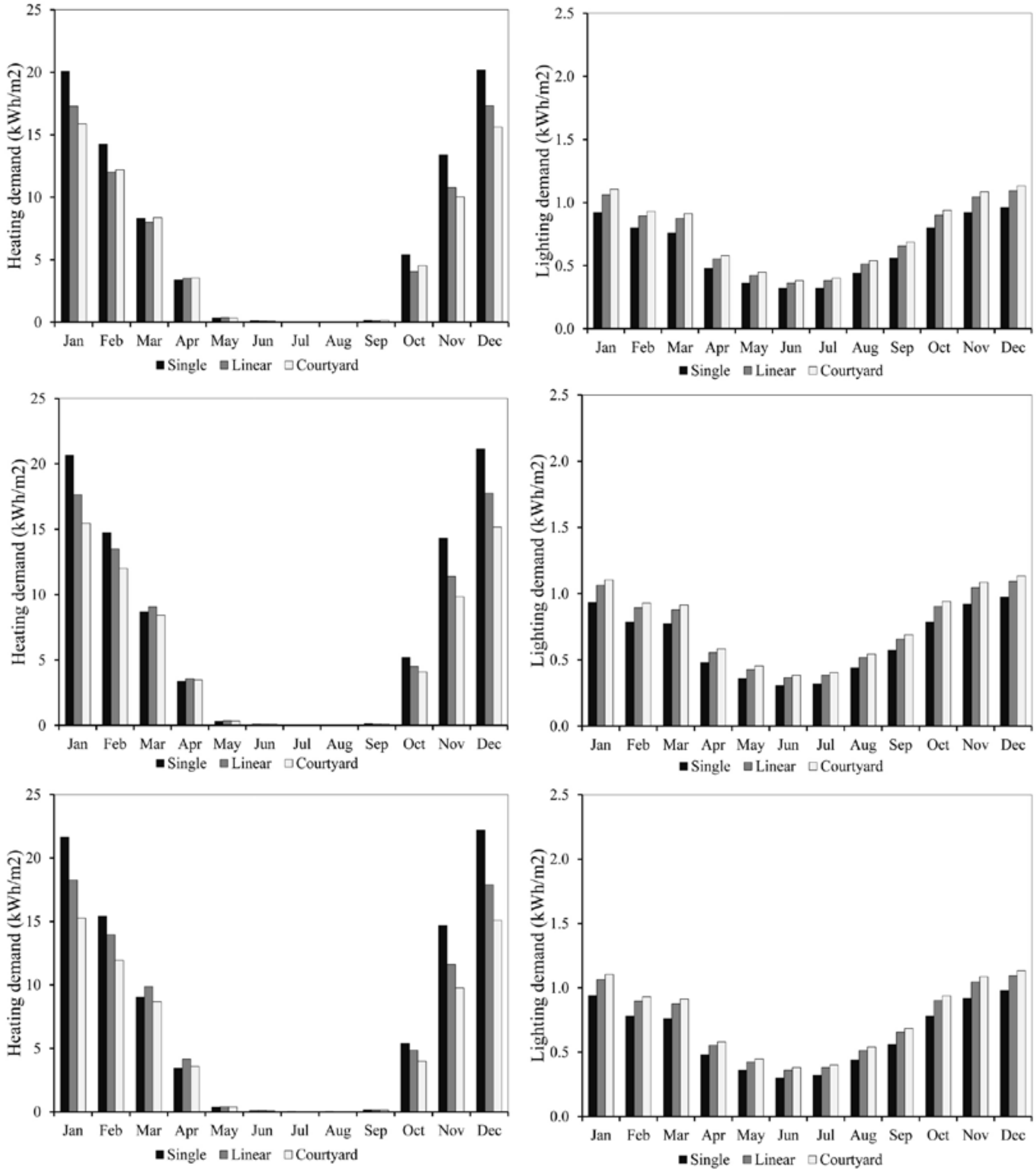

Figure 11

Heating demand in 1-storey models (top left); average of heating demand in 2-storey models (middle left); average of heating demand in 3 storey models (down left); Lighting demand in 1 storey model (top right); average of lighting demand in 2 storey models (middle right); average of lighting demand in 3 storey models (down right).

In Figure 12, the total energy demand for heating and lighting of the models is illustrated for a whole year. In the free running mode (May through September), the energy demands are more or less equal because only lighting energy is required. From April until September, the single zone shape has the least energy consumption because in this period the heating energy use is very low (nearly zero); therefore the energy demand for lighting is dominating. However, the linear and courtyard shapes consume less energy considering a whole year since their energy demand for heating is lower, reflected by a lower surface to volume ratio. In Figure 11 it is visible that the courtyard which has the smallest surface to volume ratio has a higher heating energy efficiency than the linear (and single zone) shape.

Moreover, Figure 11 shows that over the period of a full year, by increasing the number of floors of the single zone building and of the linear zone building, the energy consumption increases. For a courtyard dwelling, however, a slight decrease is visible. This is due to its low heating demand (which is also resulted by its least surface to volume ratio among the models).

If the single zone model were a reference for energy consumption, the linear and courtyard building types would show 12% and 14% energy reduction in the one-storey models, a 10% and 19% reduction in two-storey models (average of 2 floors), and a 10% and 22% reduction in three-storey models (average of 3 floors) respectively. This indicates that by increasing the number of floors, the energy saved by the courtyard models increases, compared to the other models.

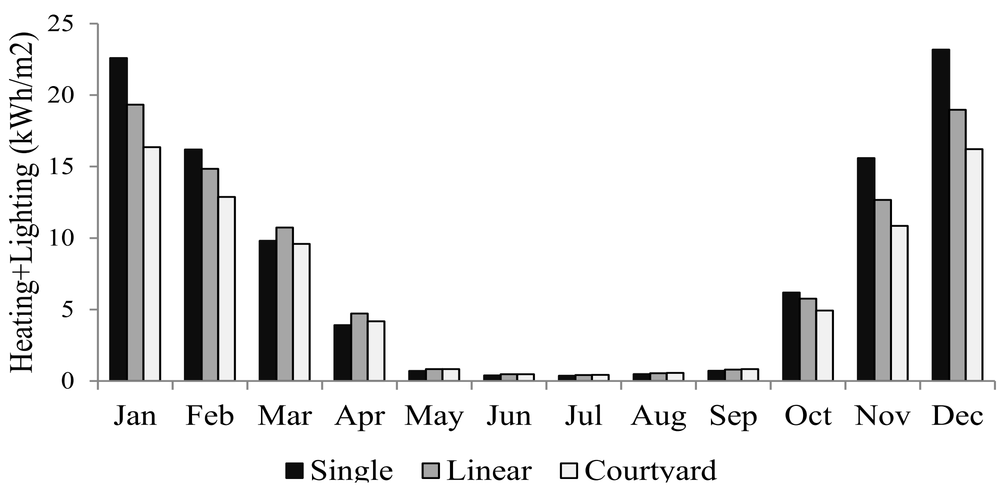

Figure 12

The sum of the annual heating and lighting energy demand of the models for a full year (average of the three storey models).

§ 4.4.2 Summer thermal comfort

§ 4.4.2.1 One-storey models

Thermal comfort was examined when the dwellings were in free running mode (May 1st – September 30th). Therefore, the hourly operative temperatures of each zone during this period were applied to the EN15251 adaptive comfort standard. The percentages of discomfort hours are calculated by dividing the total number of discomfort hours by the total number of hours that the zones are occupied in this period (153 days * 7 hours per day = 1071 hours). In Figure 13, the percentages of discomfort hours during the mentioned five months are presented separately according to EN15251.

Comparing the layouts, the single zone building has the highest percentage of discomfort hours compared to the average of the zones of the other buildings. For the linear and courtyard shapes this average is more or less equal. Referring to Table 4, the zones in the linear building on average receive 57 kWh/m^2 less solar heat gains from windows compared to the single zone building (1 storey). This difference is 75 kWh/m^2 for the courtyard building. Therefore, as discussed in the sections on energy performance, the higher the solar gain, the greater the risk of overheating and consequently the higher the number of discomfort hours.

Discussing the layouts, it is visible that the zones that are more exposed to their outdoor environment (and are less covered) are more prone to increased discomfort. In this regard, the zones located on the corners of the linear and courtyard models have less comfort hours. On this account, the linear model with two separated linear buildings shows the importance of sun exposure. Here the zones located in the southern building have higher sun gains and accordingly a higher number of discomfort hours than the northern building. These differences are repeated for the courtyard zones.

§ 4.4.2.2 Multi-storey models

The differences between the results are also visible in the multi-storey models. By increasing the number of floors, the differences in the percentage of discomfort hours between the single zone building and the other models are more significant.

Referring to the results and Figure 14, the numbers of discomfort hours rise by increasing the number of floors in the single shape zone. However, for both the linear and the courtyard shapes, the number of discomfort hours decreases with increasing the number of floors. This shows the importance of sun exposure potential in these models.

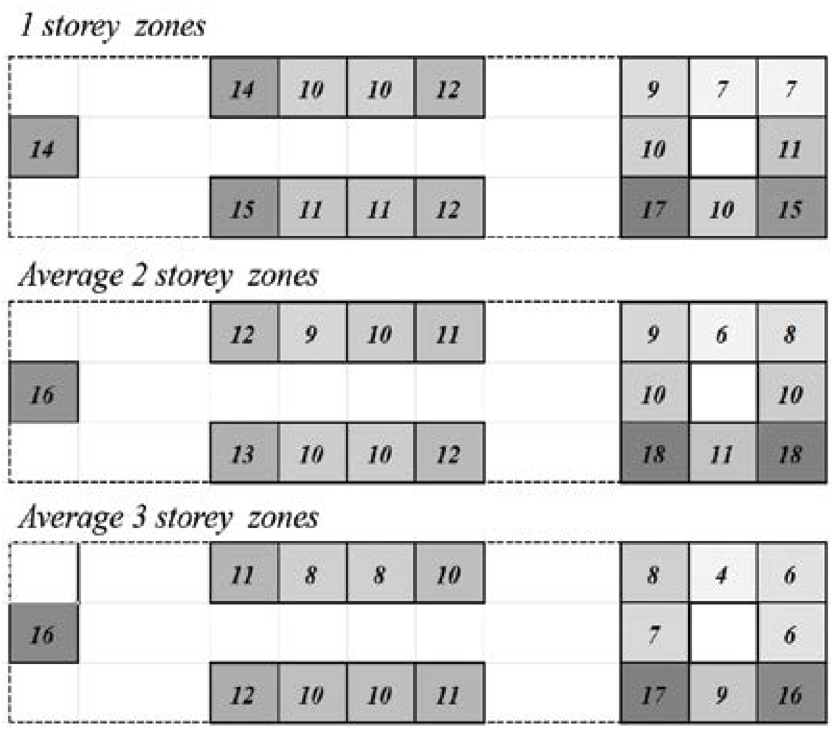

Figure 13
Percentage of discomfort hours of the models based on EN15251 in the summer period; above, the 1 storey; middle, the average of 2 storey zones; down, the average of 3 storey zones.

§ 4.4.3 Energy versus comfort

Taleghani et al. [19] made a comparison between different building forms regarding the effect of different building typologies on indoor energy and comfort. They showed, all else being equal, that the larger surface to volume ratio of a courtyard building (and its envelopes), the higher heat loss and consequently energy demand for heating compared to a building with no open space. The current research added a linear building type to these comparisons, using 1- , 2- and 3- storey models. Although [19] found the courtyard dwelling performing less energy efficiently compared to a building with a square floor plan of the same size, the present study showed that the courtyard dwelling was more energy-efficient. This discrepancy can be understood with reference to the surface to volume ratio of the dwellings with a square floor plan.

From the energy point of view, the energy consumption for heating and lighting of the single and linear shape models increases when the number of floors in the models increases. This amount is slightly decreased for the courtyard shape. On the other hand, from a thermal comfort point of view, Figure 14 shows that the single zone model has the lowest number of comfort hours while it at the same time has the highest energy consumption. This observation also applies to the 2- and 3-storey models (average of all floors). In this case, by increasing the number of floors, the average of the number of comfort hours in the single-zone building decreases. Conversely, the average of the number of comfort hours in the linear and the courtyard shape model increases by increasing the number of storeys from 1 to 3.

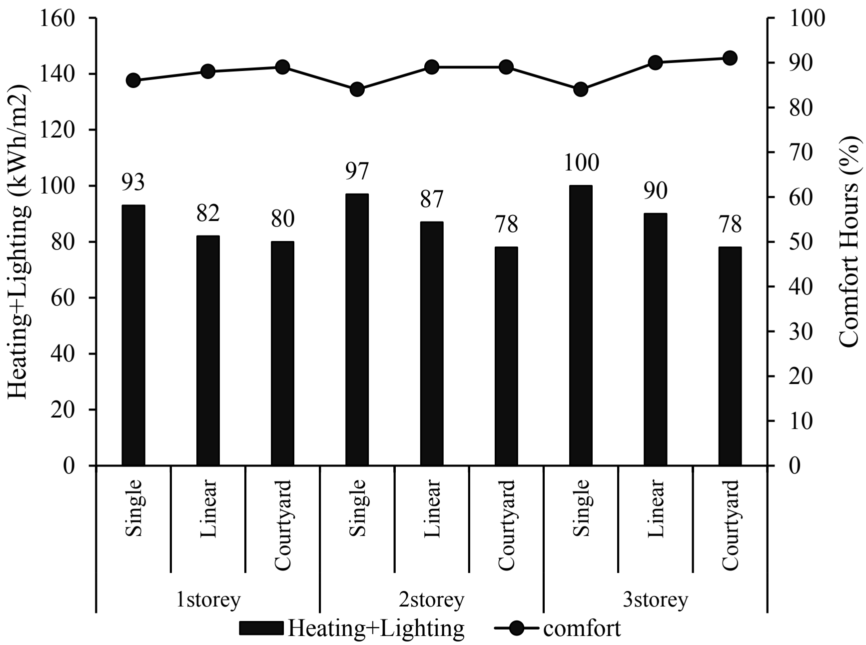

Figure 14
Heating and lighting energy demand of the models and their percentage of thermal comfort hours..

§ 4.5 Conclusion

This chapter analysed the energy and comfort performance of three types of urban blocks in the Netherlands, each with 1, 2 and 3 storey configurations. The main objective of the research was to clarify the effect of building geometry on its annual heating energy demand, daylight factor and annual lighting energy demand, heat loss, solar gains through external windows and discomfort hours during free running time (May 1st – September 30th) for Dutch dwellings based on the European thermal comfort standard (EN15251:2007).

The buildings have different surface to volume ratios owing to different shapes: single, linear and courtyard shape. Actually, the single shape model is more exposed to its outdoor environment and has the highest surface to volume ratio. The linear models are consisted of row zones which leads to a lower exposure, and this amount is the least one for the courtyard models (referring Table 2 and Figure 7). The outdoor environments of geometries analysed with CFD calculations against the prevailing wind (south west in Rotterdam) showed different reactions. This helps to a better understanding of the indoor models behaviour.

In the one storey models, the heat loss energy mostly happens for zones located in the south west corners because of the prevailing wind. Moreover, the single zone has higher surface to volume ratio and this models has the highest solar gains. In total, the average amount of heating energy demand in a year for the single shape is the highest among the models. However, the lighting energy demand for the single shape is the lowest. In this regard, the linear and courtyard models are very close in lighting energy demand. Furthermore, the range of summer thermal comfort acceptable for 80% of people (category II of EN15251:2007 standard) calculated and determined for this climate. It was found that based on the indoor operative temperature of one storey zones, the courtyard model has the least discomfort hours.

The differences between the three different floor-plan layouts in terms of heating energy demand and thermally comfortable hours were most evident in the three storey simulations. The results showed the single house has the greatest amount of daylight, and consequently, the smallest demand for lighting energy. The courtyard shape has the lowest heating energy demand since it is more protected in the temperate climate of the Netherlands. Considering thermal comfort hours in free running mode, the courtyard shape has the least discomfort hours among the models. Reducing the external surface area exposed to the climatic environment leads to higher energy efficiency and improved summer thermal comfort performance.

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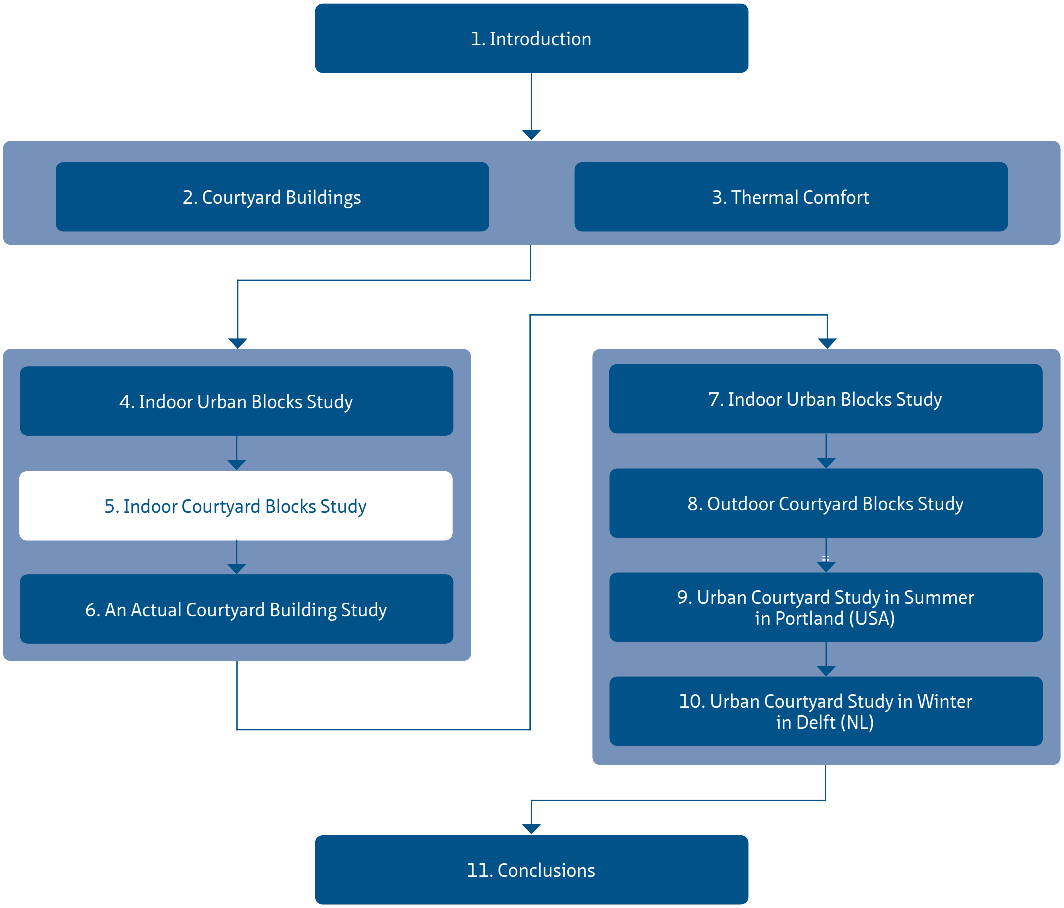
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