Energy performance and thermal comfort of courtyard/atrium dwellings in the Netherlands in the light of climate change

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Abstract

With increased global concerns on climate change, the need for innovative spaces which can provide thermal comfort and energy efficiency is also increasing. This paper analyses the effects of transitional spaces on energy performance and indoor thermal comfort of low-rise dwellings in the Netherlands, at present and projected in 2050. For this analysis the four climate scenarios for 2050 from the Royal Dutch Meteorological Institute (KNMI) were used. Including a courtyard within a Dutch terraced dwelling on the one hand showed an increase in annual heating energy demand but on the other hand a decrease in the number of summer discomfort hours. An atrium integrated into a Dutch terraced dwelling reduced the heating demand but increased the number of discomfort hours in summer. Analysing the monthly energy performance, comfort hours and the climate scenarios indicated that using an open courtyard May through October and an atrium, i.e. a covered courtyard, in the rest of the year establishes an optimum balance between energy use and summer comfort for the severest climate scenario.

Keywords

Courtyard, atrium, climate change, heating demand, thermal comfort.

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1. Introduction

1.1. Background

In the light of energy reduction, transitional spaces have been recognised as a way to receive natural light and air [1-9]. These spaces have been used for 5000 years [10, 11], and have emerged in different types for varied purposes. These spaces cover a wide range of spaces from a balcony and a corridor to a courtyard or an atrium. Transition zones are the in-between architectural spaces where the indoor and outdoor climate is moderated without mechanical control systems. In these spaces the occupant may to a certain extent experience the dynamic effects of changes in the outdoor climate. Typically transitional spaces have different interactions with the outdoor environment depending on the climate. In hot climates, they are open to the sky to ease night radiation flux [6, 12-14]. Steemer et al. [15] proposed six archetypal generic urban forms for London (51°N) and compared incident solar radiation, built potential and day-lighting criteria. They concluded that the courtyard performs best among these six archetypes. In humid regions, they are used to ventilate buildings and reduce humidity [16-19]. Okeil [20] generated a built form named the Residential Solar Block (RSB), which later was compared with a slab and a pavilion court [21]. The RSB was found to lead to an energy efficient layout for a hot and humid climate of UAE at a latitude of 25°N. Regarding the importance of ventilation in hot arid and humid climates, Al-Hemiddi and Megren Al-Saud [22] demonstrated that the cross ventilation in a courtyard results in significant enhancement of cooling the interiors and providing thermal comfort. Regarding the orientation, [23] in a hot arid environment with measurements showed that in two identically shaped and similarly treated courtyards, but differently oriented, East-West direction provides much more thermal discomfort than North-South. In colder environments, courtyards are covered and glazed to capture solar energy and reduce heat loss [24-27]. Aldawoud and Clark [5] in a comparison between courtyard and atrium in four different cities in the US showed that the open courtyard building exhibits a better energy performance for the shorter buildings, while at some point the enclosed atrium exhibits a better energy performance for tall buildings. They also discussed that different factors like glazing and climate parameters play important role in the efficiency of an atrium. Last but not least, in snow climates, a group of buildings forming an urban courtyard protects itself against cold winds [8, 28].

This paper investigates courtyards, common in hot climates, as a possible passive strategy for buildings in temperate climates. More precisely, the courtyard and the atrium (covered courtyard) as transitional spaces will be analysed in this paper to see if they could be applicable and effective for dwellings in the Netherlands by 2050. Finally, the paper will conclude whether courtyards or atria, or a combination of both, can provide a more energy-efficient and comfortable indoor environment for the temperate climate of the Netherlands. In other words, the main question for the study presented is whether the use of transitional spaces can be a solution for temperate climates if these become subject to climate change.

1.2. Climate change in the Netherlands

There is a growing concern about the use of fossil energy and its implications for the environment. After decades of debate, the human influence on the climate seems near to certain, supported by a vast majority of climate scientists gathered under the International Panel on Climate Change [29]. NASA has identified eight effects of rapid climate change. These are: global temperature rise, warming oceans, shrinking ice sheets, declining arctic sea ice, glacial retreat, sea level rise, extreme weather events and ocean acidification. The exact extent to which these effects of climate change will occur, and in which timeframe, is subject to uncertainty. Therefore the IPCC works with different variants, sets of probabilities, each leading to different outcomes for the temperature increase and sea level rise. The Royal Dutch Meteorological Institute (KNMI) has translated the IPCC variants to four main scenarios in the near future in 2050, divided as in a matrix of two times two: a moderate and warm scenario (+1^{o}C, +2^{o}C temperature increase respectively) versus unchanged or changed air circulation patterns. Figure 1 presents these four scenarios.

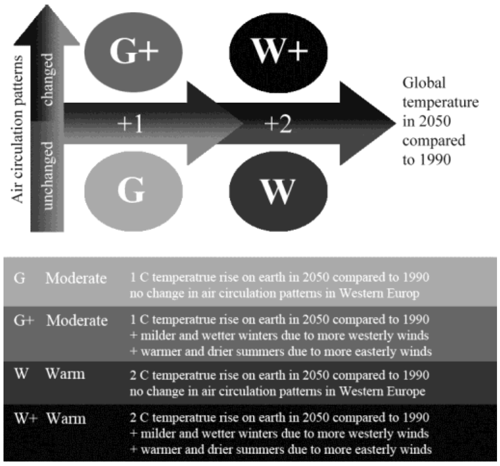

Figure 1: Four climate scenarios for the Netherlands in 2050 [30].

Based on these scenarios, Figure 2 presents the expected number of summer days with temperatures exceeding 25^{o}C (the mean temperature in the Netherlands is around 10^{o}C).

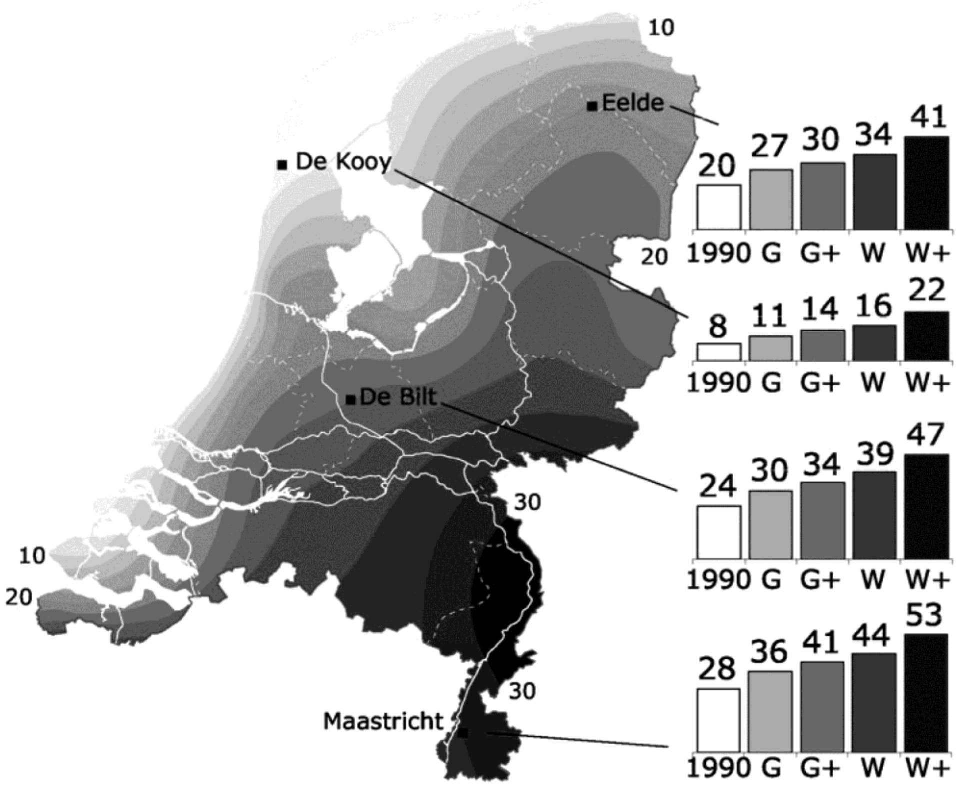

Figure 2: Calculated effects on the number of summer days in case of the four climate scenarios for the Netherlands in 2050 [30].

Table 1 presents an overview of climate characteristics for each of the four climate scenarios.

2050		G	G+	W	W+
Global temperature rise		+1°C	+1°C	+2°C	+2°C
Change in air circulation patterns		No	Yes	No	Yes
Winter	Average temperature	+0.9°C	+1.1°C	+1.8°C	+2.3°C
	Coldest winter day per year	+1.0°C	+1.5°C	+2.1°C	+2.9°C
	Average precipitation amount	+4%	+7%	+7%	+14%
	Number of wet days (≥0.1 mm)	0%	+1%	0%	+2%
	10-day precipitation sum exceeded once in 10 years	+4%	+6%	+8%	+12%
	Maximum average daily wind speed per year	0%	+2%	-1%	+4%
Summer	Average temperature	+0.9°C	+1.4°C	+1.7°C	+2.8°C
	Warmest summer day per year	+1.0°C	+1.9°C	+2.1°C	+3.8°C
	Average precipitation amount	+3%	-10%	+6%	-19%
	Number of wet days (≥0.1 mm)	-2%	-10%	-3%	-19%
	Daily precipitation sum exceeded once in 10 years	+13%	+5%	+27%	+10%
	Potential evaporation	+3%	+8%	+7%	+15%
Sea level	Absolute increase	15-25 cm	15-25 cm	20-35 cm	20-35 cm

Table 1: climate change scenarios for 2050 in the Netherlands [30].

Recent insights indicate a greater probability towards W (Warm) and W+ (Warm+) rather than G (Moderate) and G+ (Moderate +), implying higher temperatures throughout the year as well as dryer summers and wetter winters. For residential buildings, this is important, since these for indoor comfort need to be adjusted to higher outdoor temperatures. Preferably this needs to be done without mechanical interventions, because correction by means of air-conditioning units would increase the consumption of fossil fuels, thereby further aggravating climate change and heating up urban areas locally due to waste heat from the cooling device. Another consequence of the most probable scenarios is an increase of precipitation in winter and heavier showers in summer, which in a common Dutch situation would be discharged as quickly as possible, but this now already creates flood problems, so local retention will become necessary.

2. Methodology

2.1. Modelling and simulations

This simulation study is divided into four phases, each showing the effect of using a transitional space inside a building (see Figure 3). Phase zero forms the reference for this study and uses a typical Dutch mid-terraced dwelling without any form of transitional space. In phase 1, two courtyard models are introduced; the first is an existing dwelling located in Amsterdam (Figures 5 and 6) and having a small courtyard, i.e. a patio; the second is a virtual dwelling that was constructed by introducing a small courtyard in the Dutch mid-terraced reference dwelling (Figure 4). In phase 2, the courtyards of the dwellings from phase 1 are covered with a glazed roof, creating an atrium. In the last phase, the courtyards of the dwellings from phase 1 have a glazed roof in winter (from October till April) and no roof in summer (from May till September). All models are designed in such a way that they at least have a living room, a bedroom and a kitchen.

For the simulations the DesignBuilder software package was used, which employs the state-of-the-art building performance simulation engine of EnergyPlus. EnergyPlus is a comprehensive transient simulation tool including detailed accounting of energy inputs and energy losses. The simulation is based on hourly weather data and among others takes into account solar heat gains through windows, heat conduction and convection between different zones and the energy applied or extracted by mechanical systems [31, 32].

Model	Surface/Volume
Reference model	0.38
Amsterdam courtyard	0.51
Virtual courtyard	0.88

Table 2: (Envelope) surface to (interior) volume ratio of the models.

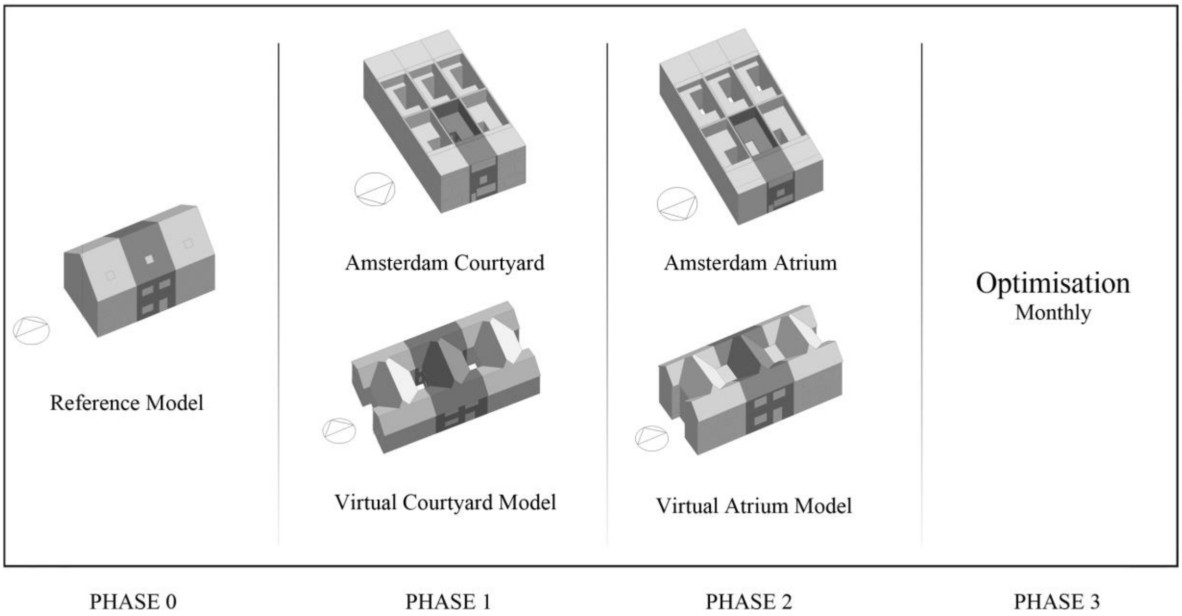

Figure 3: the research scenario.

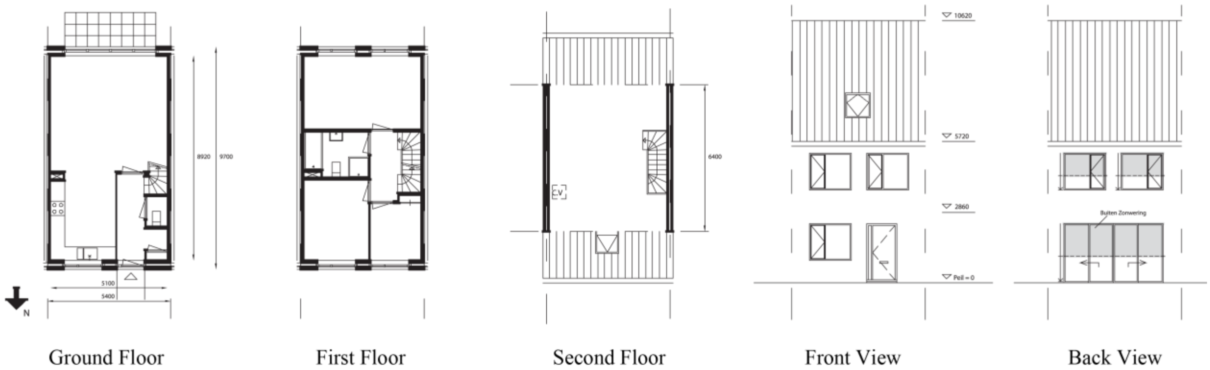

Figure 4: The Dutch Agentschap NL mid-terraced reference dwellings [33].

Figure 5: The Amsterdam courtyard dwelling (images from Google Map).

Ground Floor First Floor Second Floor Cross Section

Figure 6: The Amsterdam courtyard house with its left and right adjacent.

For this study, the following properties were implemented in DesignBuilder:

a) Construction:

For the simulations, the wall and roof types were parameterised with the data in Table 3.

Section	*U*-value W/m^{2}K	R_c-value m^{2}K/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 roofing felt (2mm) - Fibreboard (13mm) - XPS Extruded Polystyrene (80mm) - Cast Concrete (100mm) - Gypsum Plastering (15mm)	0.33	2.9

Table 3: the wall and roof properties used in the simulations and calculations.

b) HVAC:

The heating system considered in the models is based on radiators for which the water is supplied by a gas boiler with an efficiency of 65%. The heating set points are described in Table 4, and the heating set-backs are 12^{o}C.

Regarding the ventilation, the dwellings have a natural supply of fresh air. Moreover, if the indoor air temperature has risen to above 22^{o}C windows (15%) are opened for cooling.

Furthermore, the wind factor used is 1.00. The models are not equipped with an additional mechanical cooling system since the predominant part of Dutch dwellings are in free running mode during summer. Furthermore, there is an operation schedule for the zones. The operating schedule specifies the times when the prescribed environmental conditions should be met.

	Heating schedule	Set-point °C
Living room	16:00-23:00	21
Bedroom	22:00-09:00	18
Kitchen	16:00-23:00	18

Table 4: heating schedules, set points and set backs of the thermal zones.

c) Glazing type and lighting:

Most Dutch dwellings have large windows to achieve maximum daylight access. This is mostly because of the high latitude (52^{o}N) and consequently the low sun angle during the winter (15^{o} at 12:00 on 21st of Dec). A window-to-wall ratio of around 30% is very common in the Netherlands. The external window type for the models is double glazing (generic clear 3mm) with an air cavity of 13mm in between the layers (U- value= 1.96 W/m^{2}K).

2.2. Summer thermal comfort calculation

Thermal comfort temperature boundaries reflect within which temperature range the indoor environment is assumed to be comfortable for users [34, 35]. Among all thermal comfort standards, this study uses ASHRAE 55-2010 for the calculations of summer thermal comfort. This is due to the large number of field studies making up its database. Moreover, recent studies [36-41] have compared several thermal comfort standards with different approaches; however, [42] showed that ASHRAE estimations were closer to the actual mean votes. The main purpose of this standard is to specify the combinations of indoor thermal environmental parameters (temperature, thermal radiation, humidity and air speed) and personal parameters (clothing insulation and metabolism rate) that will produce thermal environmental conditions acceptable to a majority of the occupants. This standard uses the following equation for calculating the indoor comfort temperature (T_{co}) based on the outdoor reference temperature (T_{ref}):

$$T_{CO} = 0.31 * T_{ref} + 17.8\ °C \qquad (1)$$

Where

T_{ref} = prevailing mean outdoor air temperature for a time period between last 7 to 30 days before the day in question [43].

This equation may be used for summer when the outdoor drybulb temperatures range from 5°C to 32°C. Figure 7 shows the comfort bandwidths derived from equation (1). Based on 80% and 90% occupant acceptability ranges. The 80% acceptability limits are for typical applications and the 90% limit may be used when a higher standard of thermal comfort is desired. Moreover, the activity level is determined as being less than 1.3 met (normally sedentary activities).

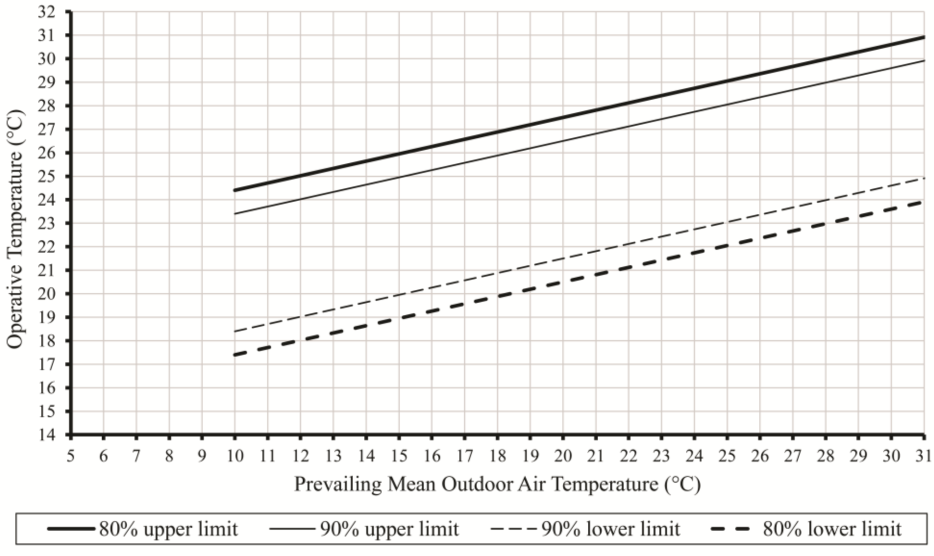

Figure 7: Comfort bandwidths of ASHRAE 55-2010 [43].

2.3. Weather data

- The current climate:

The climate of De Bilt (52°N, 4°E), representing the climate of the Netherlands, is known as a temperate climate based on the climatic classification of Köppen-Geiger [44]. The prevailing wind is South-West. The mean annual dry bulb temperature is 10.5°C (Figure 8). In this paper, the reference weather data of De Bilt is used according to Dutch standard [45]. According to this standard, every month of the reference year is represented by a specific year which is considered representative of the period from 1986 until 2005. The selection is presented in Table 5. Data files from appendix A2 (of the standard) are used for this study because these were developed for energy performance simulations. For summer thermal comfort studies, the standard [45] specifies separate weather files. In this study, also the weather file in Appendix A2 was used.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	2003	2004	1992	2002	1986	2000	2002	2000	1992	2004	2001	2003

Table 5: Representative weather data of De Bilt as used in the calculations.

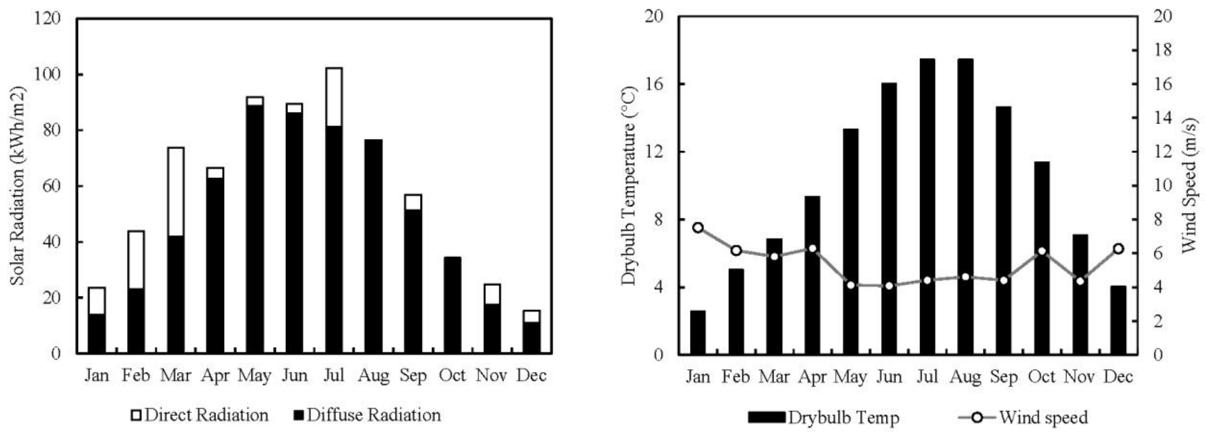

Figure 8: Climatic data of De Bilt as used for calculations and simulations.

Furthermore, based on the comfort algorithm and the range permitted for 80% of acceptability, Figure 9 presents the indoor operative comfort temperatures during the free running mode period in De Bilt. The duration of this period is based on the former Dutch energy performance standard for residential buildings [46]. This standard states that the free running mode typically occurs from 1st of May until 30th of September in the Netherlands.

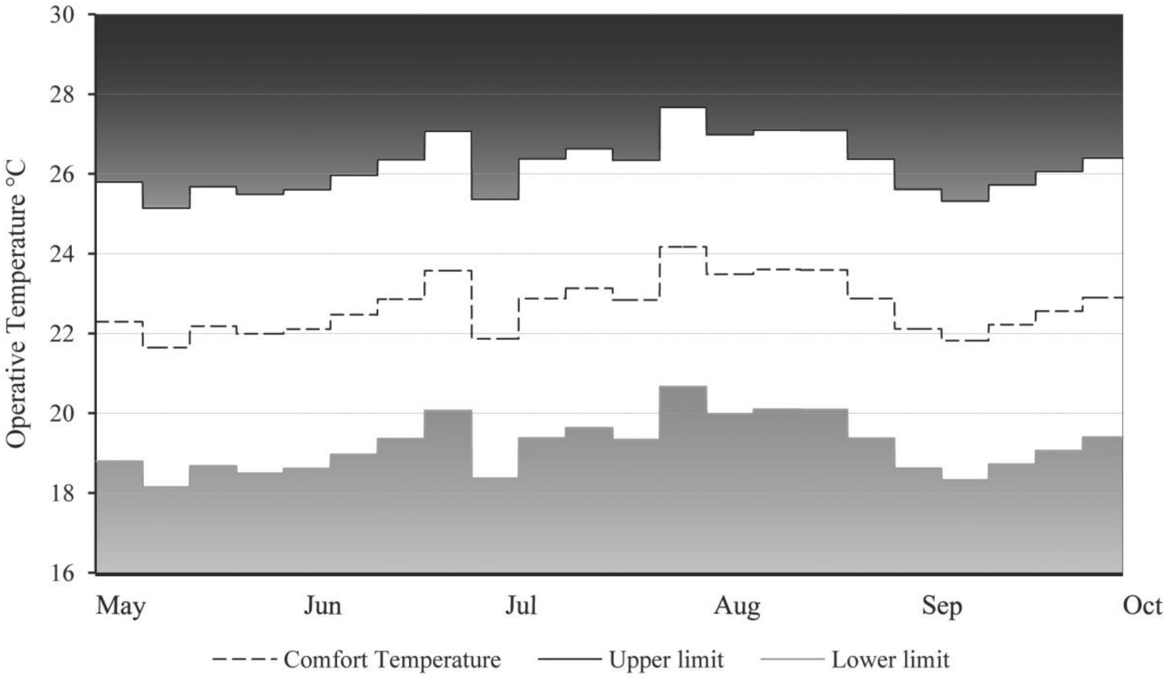

Figure 9: Comfort temperatures of De Bilt in the free running time calculated based on ASHRAE 55-2010 standard for 80% of occupants.

- Weather data for the year 2050:

In 2006, the Royal Netherlands Meteorological Institute presented the most recent climate scenarios for the Netherlands [30]. These four differing climate scenarios present the expected climate changes in the Netherlands in 2050 and 2100. The scenarios differ in the extent to which the global temperature increases and in the way wind patterns above the Netherlands change. The W and W+ scenarios are characterised by a big increase of average global temperature, whereas the G and G+ scenarios are characterised by a moderate increase of average global temperature. Moreover, contrary to the W and G scenarios, the W+ and G+ scenarios are also affected by changes in wind patterns above the Atlantic and Western Europe, causing hot and wet winters and hot and dry summers in the Netherlands.

As can be seen from Table 1, the four climate scenarios include changes in temperature, wind and precipitation, and consequently sun hours. The first and last are most important for determining the energy performance of buildings, whereas the second and third are less important. For the year 2050 and with reference to the year 1990, the climate scenarios predict an increase in temperature between 0.9°C to 2.3°C in winter and 0.9°C and 2.8°C in summer. The climate scenarios do not present a precise prediction for changes in solar radiation patterns. According to a KNMI climate sketchbook [47], the Netherlands is located at the boundary between Southern Europe, where cloud coverage will decrease, and Northern Europe, where cloud coverage will increase. Only, in the G+ and W+ small changes in the number of rainy days in summer, an consequently sun hours, are expected. In general, though, it is expected that changes in solar radiation patterns will be small. As a result, such changes are not considered in this study.

For the energy performance simulations, hourly weather data including outdoor temperature and solar radiation are needed. As explained previously, the weather file from [45] is used for simulating the current climate. This weather file is also used as a basis for the developing the weather files of 2050 for each of the four climate scenarios; only the outdoor temperature has to be modified. The weather files were developed by [48] using the KNMI online transformation program for time series [49]. This transformation tool transforms historic temperature series on a daily basis to a new series that fits one of the four climate scenarios for a certain time horizon. The procedure is as follows:

- In the transformation program, the weather station of De Bilt was selected with a time horizon of 1990. This produces the daily average temperature in De Bilt between 1976 and 2005.
- With the help of the program the daily temperatures of 1990 are then transformed to the time horizon of 2050 for each of the four climate scenarios. This produces the daily temperature in De Bilt between 2036 and 2065.
- Next, for each day in the period 1976 to 2005, the daily temperature increase over a period of 60 years (from 1976-2005 to 2036-2065) is calculated, again for each climate scenario.
- The hourly weather data in a certain month in the weather file of [45] are measured data coming from a certain representative month between the years 1986 and 2004 (Table 5). For each day in the weather file of [45] the results of the previous step are used to see how big the increase in temperature is according to each of the scenarios.
- Finally, for each day in the [45] weather file, the temperature of each hour is increased by its respective daily increase in order to get the temperature corresponding to a certain climate scenario.

3. Results and discussion

3.1. Phase zero: The reference model- Building I

The Netherlands is known as a temperate climate. As can be seen in Figure 8, in winter, the average wind speed is higher than in summer. Wind is important for the heat loss of a building by infiltration. Figure 10 shows the monthly heat loss, solar gains and heating energy demand of Building I for the current representative weather data of De Bilt [45]. The heating demand in January is around 8 kWh/m^2 (floor area). When the dwelling is in free-running mode (May-September), heating demand is zero, and during this period, solar gains through windows and internal heat gains make up for the transmission and ventilation/infiltration heat losses. Due to the increase of wind speed, the decrease of the outdoor temperature and the decrease of solar gains, the heating energy demand starts to increase from October.

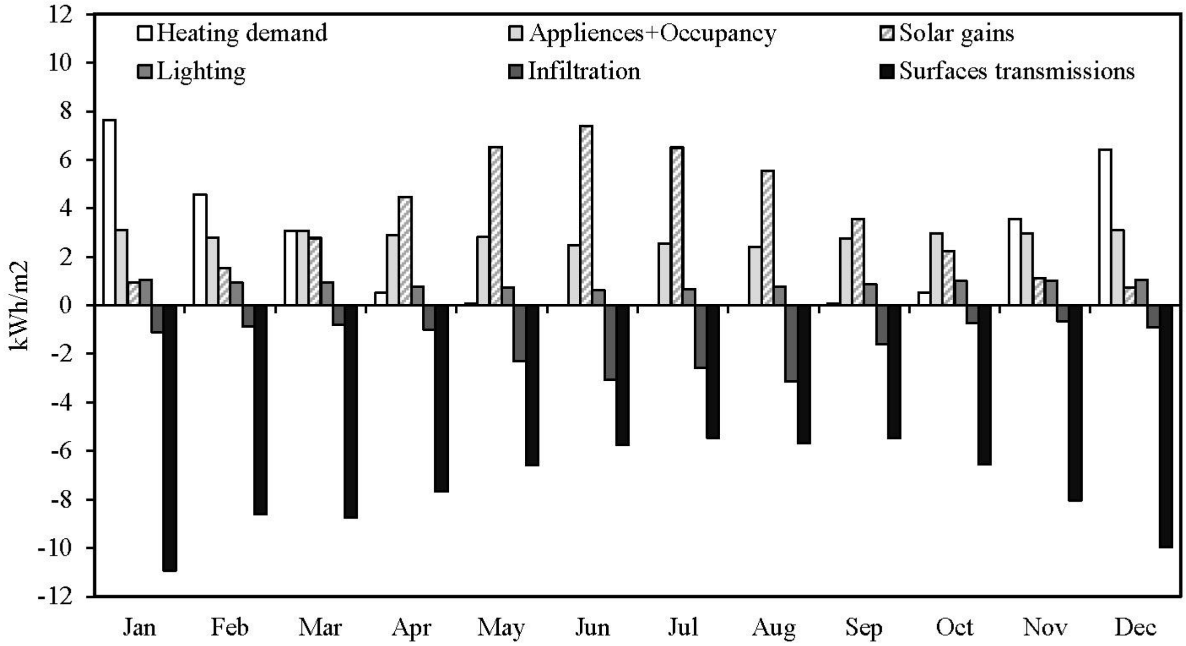

Figure 10: Monthly energy balance of the reference model representative for the current climate.

Based on this model in DesignBuilder, the four climate scenarios G, G+, W and W+ were simulated additionally. These simulations help to understand how climate change affects the dwelling’s indoor environment and energy use. Figure 11 depicts the indoor operative temperature of Building I for the current climate of the Netherlands and for each of the four climate scenarios. As illustrated, the indoor operative temperature is more or less identical in winter for each situation. The main reason is that in winter this temperature is not so much affected by the outdoor conditions but by the heating system. However, during the free-running time, the indoor operative temperature differs for each scenario. In this period, the models are not conditioned and their indoor environment mainly depends on outdoor conditions. The highest indoor operative temperature increase, equal to 2.5°C, can be found in the W+ scenario in the months June, July and August. For that scenario, the monthly average outdoor dry bulb temperature increase approximately equals 3.0°C in the respective months. Likewise, the heating energy demands based on the five sets of weather data are demonstrated in Figure 12. It is logical that less energy is needed for heating in winter if the outdoor temperature is higher. Consequently, the heating energy demand of Building I based on the representative weather data of [45] is the highest (26 kWh/m^2/yr). Also, heating energy demand is the lowest for the severest climate scenario (W+): 19 kWh/m^2/yr.

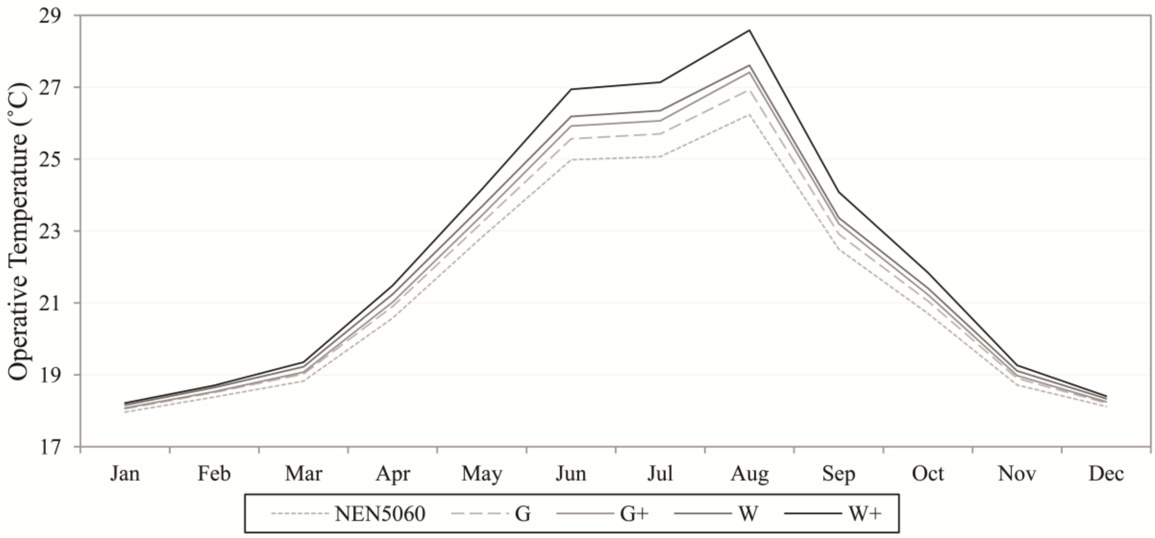

Figure 11: Monthly average Indoor operative temperature of Building I versus outside dry bulb temperature based on [45] and the four KNMI'06 climate scenarios.

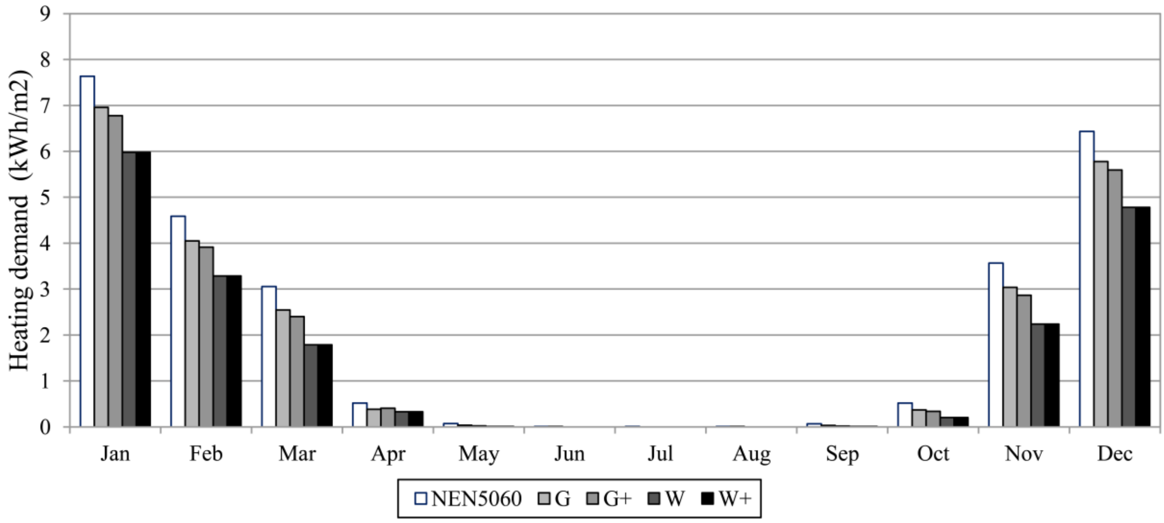

Figure 12: Heating energy demand of Building I based on [45] and the four KNMI'06 climate scenarios.

Because of the increase of indoor operative temperature during free-running time, the number of thermally comfortable hours changes. In this regard, the indoor comfort temperature and the range for 80% satisfaction in the climate of De Bilt are important. Calculations using the adaptive thermal comfort model from ASHRAE 55-2010 for the daytime show that by the increase of outdoor drybulb temperature, the number of hours the indoor temperature exceeds the 80% satisfaction range increases from 46 hours (for the current climate) to 331 hours (for the severest scenario; W+), which equals respectively 4% and 31% of the total number of hours.

3.2. Phase one: The effect(s) of a courtyard- Buildings IIc and IIIc

At this step of the research, the effect of having a courtyard as a transitional space inside a dwelling is studied. On this account, an actual courtyard dwelling in Amsterdam-Building IIc (Figure 6), and a virtual courtyard dwelling-Building IIIc based on the reference dwelling are simulated. The simulated monthly heating energy demands of these three models are depicted in Figure 13 using the weather data representing the current climate and climate scenario W+. Based on the results, Building IIIc has a higher heating demand than Building I (45 and 26 kWh/m^2/yr respectively). Moreover, Building IIc is also less energy-efficient than Building I (33 compared to 26 kWh/m^2/yr).

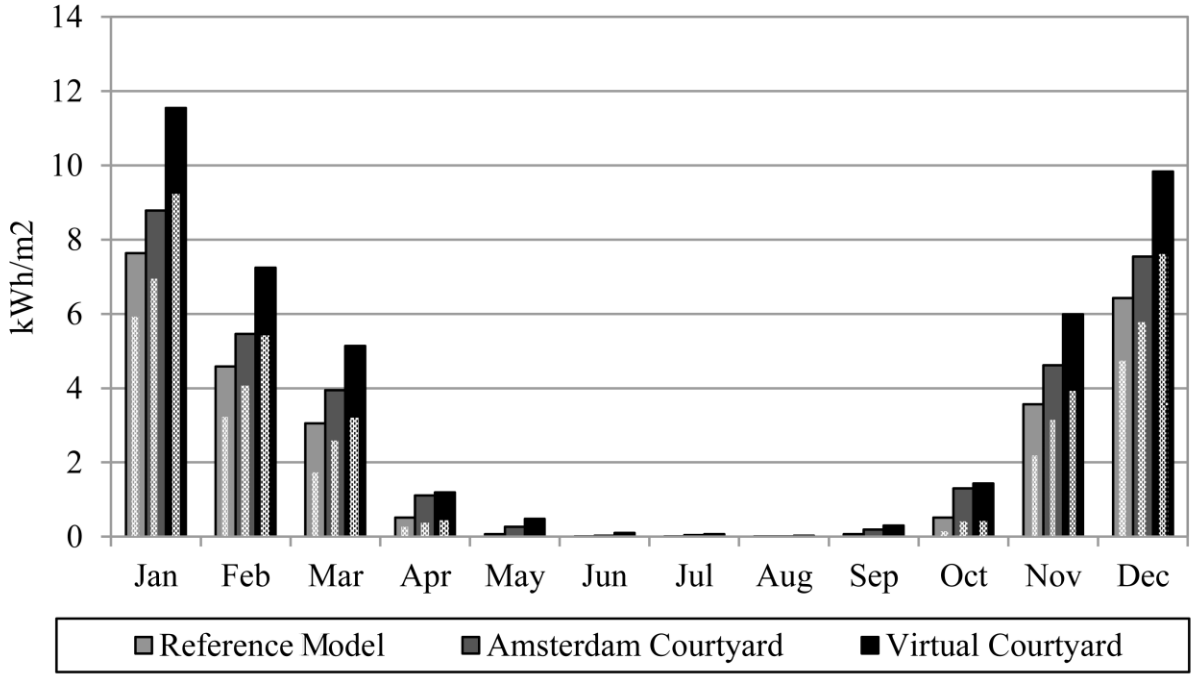

Figure 13: Heating energy demand of Building I, IIc and IIIc for the current climate of the Netherlands (dark bars) and the future W+ scenario (white bars inside dark ones).

Referring to Table 2, the surface to volume ratios of the two models in phase one are higher than Building I. This leads to the higher exposure of the models to outdoor conditions and consequently to higher heat losses in winter. In this regard, although a courtyard increases solar gains, it makes the models prone to additional transmission, ventilation and infiltration heat losses. The heating energy demands of the mentioned models in the context of climate scenario W+ are shown as white bars in Figure 13. With the increase of outdoor temperature, the heating energy demands are consequently decreased. The average reductions during a year for the models are 1.1 kWh/m^2 for Building I, 1.3 kWh/m^2 for Building IIc, and 1.7°C for Building IIIc. These differences also show how surface to volume ratio relates the heating demand of a building to its outdoor environment.

From the summer thermal comfort point of view, the indoor operative temperature of the models needs to be analysed and compared. In Figure 14, the indoor operative temperatures of Building I, IIc and IIIc are illustrated in the context of the current and the severest climate scenario (W+). Comparing Building I and Building IIIc during May-October, the indoor operative temperature of Building I is 1°C and 3°C higher than of Building IIc in the current climate and W+ scenario. Moreover, Building II has the lowest indoor operative temperature in summer. These differences between Building I and the courtyard models are due to the transmission losses through the envelopes. Apparently, since the courtyard models have a higher surface to volume ratios, they are easily prone to heat loss and ventilation. Based on the calculated comfort temperatures for this period of 5 months, Building IIc has the smallest number of discomfort hours in the severest climate scenario W+ (12% of the occupied hours), and Building IIIc made based on Building I has slightly more discomfort hours (15% of the occupied hours). As shown previously, Building I has the largest number of discomfort hours (31% of occupied hours) for this scenario.

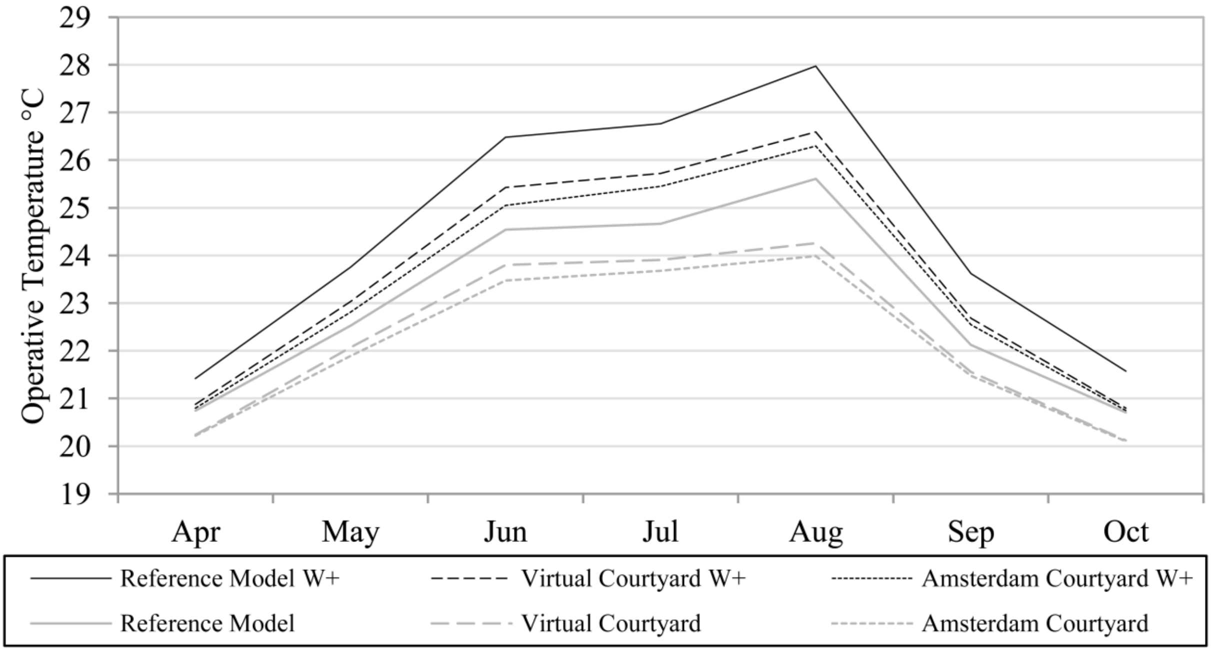

Figure 14: Monthly average indoor operative temperature of the studied models in the context of the severest KNMI'06 climate scenario (W+).

3.3. Phase two: The effect(s) of an atrium- Buildings IIa and IIIa

In this phase, the models simulated in phase one with a courtyard are covered with a glass roof (U-value of 2.2 W/m^2K). In phase one, the simulated dwellings with a courtyard showed an increase in heating demand in comparison to Building I. In this step, the courtyards are covered to analyse whether this strategy increases the efficiency of the dwellings from an energy use and thermal comfort point of view.

Referring to Figure 15, the heating demands of the courtyard dwellings (IIc and IIIc) are compared with the respective atrium models (IIa and IIIa) in the current climate of the Netherlands. During the cold months, the differences are clearly visible. In this regard, the average winter monthly heating demand of Building IIc is 1.3 kWh/m^2 more than of its atrium model (excluding summer months in which the heating demand is zero). The average winter monthly difference for Buildings IIIc and IIIa is 2.3 kWh/m^2. This shows that in a temperate climate covering the transitional space, thereby creating an atrium, can reduce the heating demand by 6 and11 kWh/m^2 for the whole year for Building IIc and IIIc, respectively. Having the models in the severest KNMI'06 climate scenario (W+), the heating energy demands have been reduced (as visible in Figure 15 with white bars). The average reductions during a year for the models between the current climate and future climate scenario W+ are 1.0 kWh/m^2 for Building IIa model, and 1.2 kWh/m^2 for Building IIIa. These differences also show how surface to volume ratio relates the heating demand of a building to its outdoor environment. Also overheating risk should be checked for atria which typically increase the number of summer discomfort hours. Therefore, similarly as in Phase one, the indoor operative temperature of the four models (being the courtyard and atrium dwellings) is compared for both the current Dutch climate and the severest KNMI'06 climate scenario (W+).

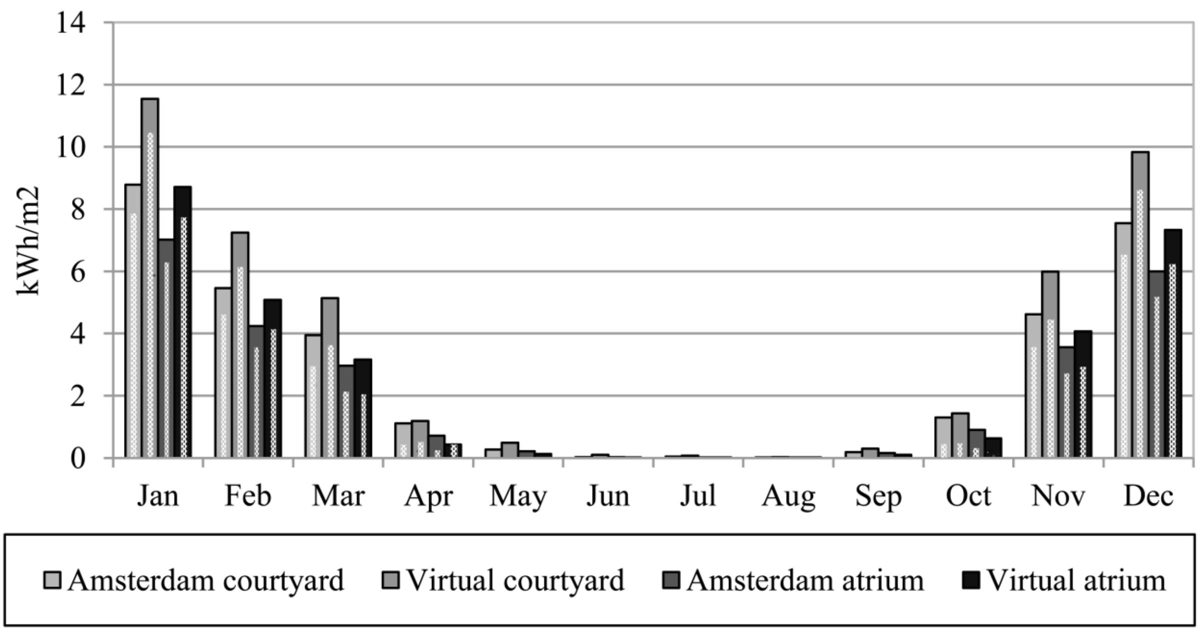

Figure 15: Monthly heating energy demand of the courtyard and atrium dwellings for the current climate of the Netherlands (dark bars) and the future W+ scenario (white bars inside dark ones).

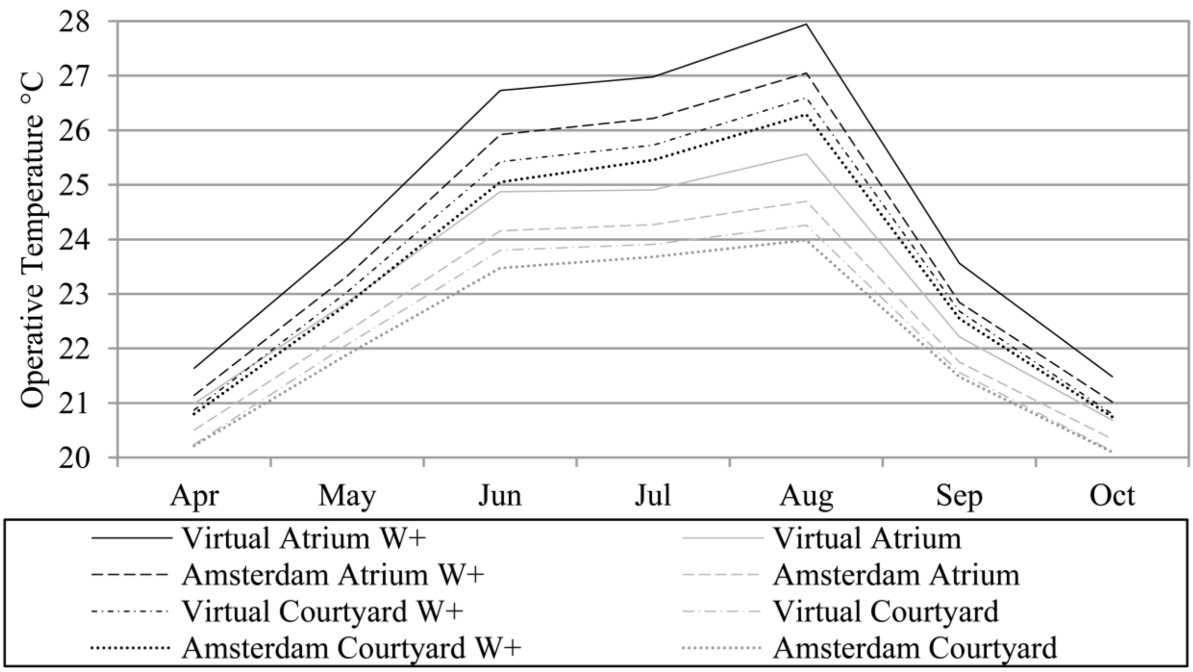

Figure 16: Indoor operative temperature of the studied models in the context of the severest KNMI'06 climate scenario (W+).

Figure 16 clearly shows how the average monthly indoor operative temperature increases during summer in the atrium dwellings compared to the courtyard dwellings for the current climate and KNMI'06 W+ climate scenario. As the monthly operative temperatures of models are depicted, converting courtyard models to atrium, increases indoor operative temperature. In this regard, the courtyard model (Building IIc) is 0.5°C cooler than the similar atrium model (during May-October). This difference in Building IIIc is 1.0°C. In general, it shows covering a courtyard and converting it to an atrium, makes the indoor environment warmer. In addition, the mentioned models in the context of KNMI'06 W+ climate scenario are considered. On this account, Building IIa is 0.6°C warmer than IIc, and Building IIIa is 1.2°C warmer than the similar courtyard model (Building IIIc). These differences cause a higher number of discomfort hours in the atrium models.

As an illustration, thermal discomfort increased from 12 to 20% for Building IIa, and 15to 33% for Building IIIa, as compared to their respective courtyard model (for the KNMI'06 climate scenario W+).

Month	Building IIc		Building IIa		Building IIIc		Building IIIa		Priority based model
	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	
Jan	9	-	7	-	12	-	9	-	At*
Feb	5	-	4	-	7	-	5	-	At
Mar	4	-	3	-	5	-	3	-	At
Apr	1	0	1	0	1	0	0	0	At
May	0	0	0	0	0	0	0	16	Cy**
Jun	0	26	0	41	0	31	0	66	Cy
Jul	0	14	0	24	0	22	0	48	Cy
Aug	0	5	0	14	0	5	0	38	Cy
Sep	0	0	0	0	0	0	0	0	Cy/At
Oct	1	0	1	0	1	0	1	0	CY/At
Nov	5	-	4	-	6	-	4	-	AT
Dec	8	-	6	-	10	-	7	-	AT
Total	33	45	26	79	43	58	30	168	-

Table 6: Monthly heating energy demand and discomfort hours (based on the current climate scenario). At*=atrium; Cy**= courtyard.

Month	Building IIc		Building IIa		Building IIIc		Building IIIa		Priority based model
	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	
Jan	7	-	6	-	9	-	7	-	At
Feb	4	-	3	-	5	-	4	-	At

Mar	3	-	2	-	3	-	2	-	At
Apr	0	0	0	0	0	0	0	0	Cy/At
May	0	2	0	12	0	8	0	34	Cy
Jun	0	58	0	75	0	63	0	106	Cy
Jul	0	40	0	62	0	52	0	84	Cy
Aug	0	27	0	62	0	43	0	125	Cy
Sep	0	0	0	0	0	0	0	2	Cy/At
Oct	0	0	0	0	0	0	0	0	CY/At
Nov	3	-	2	-	4	-	3	-	AT
Dec	6	-	5	-	8	-	6	-	AT
Total	23	127	18	211	29	166	22	351	-

Table 7: Monthly heating energy demand and discomfort hours (based on the W+ climate scenario).

3.4. Phase three: Optimisation

As shown in the previous sections, adding an atrium to a dwelling decreases its annual energy use but increases the number of discomfort hours in summer. Contrary, adding a courtyard to a dwelling increases its annual energy use but decreases the number of discomfort hours in summer. At this stage, it is tried to combine the models simulated in phases one and two to optimise for both energy use and summer thermal comfort. It is assumed to have a flexible open space inside the dwellings; in winter (October till April) covered by glass to form an atrium and in summer (May till September) opened to the sky to form a courtyard. In this regard, the two mentioned aspects – annual heating energy demand and summer thermal comfort - are the main parameters for the optimisation. Therefore, in the beginning of this phase, the period of 5 typical summer months for the open transitional space will be tested, and if the results show an increase in efficiency and thermal comfort, the duration of the period will be shortened or widened.

For the first step of the optimisation, the monthly heating energy demand and the number of discomfort hours are monitored in Table 6 and 7 (for the current climate and the KNMI’06 climate scenario W+, respectively). In this regard, from the energy point of view, Building IIa is 7 kWh/m^2 (in the current climate) and 5 kWh/m^2 (in W+ climate) in a year more efficient than its respective courtyard model (Building IIc). This difference is even bigger for Building IIIa versus IIIc (13 and 7kWh/m^2, respectively). Nevertheless, having a look at the summer indoor operative temperature as illustrated in Figure 16, the number of discomfort hours in the courtyard models is less than in their respective atrium models. Therefore, the combination of the two modes (open or closed) should be precisely based on the advantages and disadvantages of monthly performance of the models.

Table 6 and 7 show for each dwelling and for each month a summary of the heating demand and number of discomfort hours based on the current climate and the KNMI’06 climate scenario W+, respectively. The last columns show which of the dwellings, atrium or courtyard situation, has the best performance concerning energy use and/or summer thermal comfort. The courtyard models have a lower number of discomfort hours and higher heating energy demand in comparison with their atrium models. Therefore, for an optimised model the advantages of the atrium should be used for winter (limiting heat losses), whereas the advantages of the courtyard should be used for summer (reducing overheating). According to the simulations, it would be efficient if the transitional space is open for about 4 to 6 months (starting in May; ending in August, September or October) and be covered for the rest of the year. For this optimised model and in the context of the current climate, the heating energy demand of Building IIo will be 26 kWh/m^2 in a year, and the discomfort percentage in summer will be 4%. For Building IIIo, it is 30 kWh/m^2/yr for heating demand and 5% for discomfort hours. Regarding the future climate scenario (W+), the heating energy demand of the Building IIo will be 18 kWh/m^2 in a year, and the discomfort percentage in summer will be 12%. Moreover, for Building IIIo it will be 22 kWh/m^2/yr for heating demand and 15% for discomfort hours.

Finally, at the end of the optimisation, it is useful to mention if all the optimisations have led to a more efficient building rather the reference model (Building I). Tables 8 and 9 compare Building I with optimised models in the contexts of current and W+ climate scenarios. Comparing the Buildings IIo and IIIo with Building I, the heating energy demands are equal while the summer discomfort hours are one third and half of Building I, respectively.

Month	Building I		Building IIo		Building IIIo	
	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours
Jan	8	-	7	-	9	-
Feb	5	-	4	-	5	-
Mar	3	-	3	-	3	-
Apr	1	0	1	0	0	0
May	0	2	0	0	0	0
Jun	0	56	0	26	0	31
Jul	0	36	0	14	0	22
Aug	0	31	0	5	0	5
Sep	0	0	0	0	0	0
Oct	1	0	1	0	1	0
Nov	4	-	4	-	4	-
Dec	6	-	6	-	7	-
Total	28	125	26	45	30	58

Table 8: Monthly heating energy demand and discomfort hours (based on the current climate scenario).

Month	Building I		Building IIo		Building IIIo	
	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours	Heating kWh/m2	Discomfort hours
Jan	6	-	6	-	7	-
Feb	3	-	3	-	4	-
Mar	2	-	2	-	2	-
Apr	0	0	0	0	0	0
May	0	28	0	2	0	8
Jun	0	96	0	58	0	63
Jul	0	73	0	40	0	52
Aug	0	134	0	27	0	43
Sep	0	0	0	0	0	0
Oct	0	0	0	0	0	0
Nov	2	-	2	-	3	-
Dec	5	-	5	-	6	-
Total	18	331	18	127	22	166

Table 9: Monthly heating energy demand and discomfort hours (based on the W+ climate scenario).

4. Conclusions

In this paper, the effects of transitional spaces on the annual heating energy demand and summer thermal comfort were discussed. A Dutch mid-terraced dwelling was selected as a reference model- Building I (based on AgenstchapNL; Netherlands Ministry of Economic Affairs). As phase zero, this model was simulated in the contexts of five weather conditions in the Netherlands. The first one is representative of the current climate; the other four represent four climate scenarios for the Netherlands in 2050: G (moderate), G+ (moderate, changed air patterns), W (warm), and W+ (warm, changed air patterns). Reasonably, the simulations showed that because of climate change, the heating energy demand of Building I decreases and the number of discomfort hours in summer increases.

Therefore, in the next phase, the effect of a courtyard or patio was tested to see if it can increase the energy efficiency or indoor summer thermal comfort. In this regard, an actual courtyard dwelling in Amsterdam (Building IIc) and a virtual courtyard dwelling (Building IIIc developed from the reference model) were simulated. The results showed that the courtyard reduces the indoor operative temperature in summer, and consequently the number of discomfort hours, but increases the annual heating demand of the dwelling.

Therefore, in the next phase of the study, the courtyards were covered by a glazed roof to reduce the heat losses in winter. Covering the courtyard indeed led to a lower heating energy consumption of the models but also led to more thermal discomfort in summer. Finally, in the last phase, the advantages of the courtyard and atrium models were the subjects for optimisation. This optimisation was based on the monthly behaviour of the models. A combined model was introduced optimising the monthly heating energy demand in winter and thermal discomfort in summer. Simulations showed that the optimal period of having an open courtyard is at least between the four months of May until August. In the period from November until April, the courtyard should be covered with glass. Due to the moderate situation in September and October, both the courtyard or atrium modes perform equally well. Comparing the optimised Amsterdam (Building IIo) and virtual models (Building IIIo) with the reference model (Building I), the heating energy demands are equal while the summer discomfort hours are one third and half of the reference model, respectively.

Consequently, this paper showed that climate change influences heating energy demand and summer thermal comfort. Open transitional spaces can be a way to reduce overheating. Moreover, the application of these spaces should be in consideration of winter to avoid heat losses. Consequently, the most important finding of this paper indicates that the best duration for using an open space in a year in the specific climate the Netherlands is between May and August (and can last till October).

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