Proceedings of 7th Windsor Conference: ***The changing context of comfort in an unpredictable world*** Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

The Effect of Different Transitional Spaces on Thermal Comfort and Energy Consumption of Residential Buildings

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Abstract:

Purpose- This paper focuses on the effect of courtyards, atria and sunspaces on indoor thermal comfort and energy consumption for heating and cooling. One of the most important purposes is to understand if certain transitional spaces can reduce the energy consumption of and improve thermal comfort in houses.

Method of Research- To conduct this research, 4 building types were modelled and simulated in three different climates with DesignBuilder. From these simulations, the energy consumption of the dwellings is determined. Moreover, the indoor temperature data were plotted on adaptive temperature boundary charts.

Findings- This paper shows that a courtyard is the least efficient dwelling type for the Netherlands, while an atrium has better energy efficiency and indoor thermal comfort. Moreover, a sunspace is not recommended for the hotter climates of Cairo and Barcelona since there is a risk of overheating in summer. The paper also reports that although a building type may not be energy-efficient (in comparison with other types), it may still provide a comfortable addition to a dwelling.

Keywords:

Energy consumption, Thermal comfort, Transitional spaces, Residential building.

1. Introduction

Transitional spaces are potentially and traditionally efficient ways to moderate indoor climate with the free sources available from nature. These kinds of spaces are recently being considered from the comfort point of view. In this regard, the current study focuses on three different transitional spaces: courtyards, atria and sunspaces. A courtyard is an unroofed area which is – in this study – located at the centre of a building, and thus surrounded from four sides. An atrium is identical to a courtyard with the exception that it has a glazed roof on top of it. The sunspace also has the same configurations as the atrium, however, having fully glazed walls. These three building types will be compared to a reference building (as a reference) in regards to: a) energy consumption for heating and cooling, and b) thermal comfort.

Transitional space	Related reference(s)
Courtyards	(Aldawoud, 2008; Brown & DeKay, 2001; Givoni, 1991; Muhaisen, 2010; Reynolds, 2002; Schoenauer & Seeman, 1962)
Atria	(Chow & Wong, 1999; Göçer et al., 2006; Holford & Hunt, 2003; Mills, 1994; Sharples & Lash, 2007)
Sunspaces	(Baleynaud et al., 1991; Bataineh & Fayez, 2011; Mihalakakou, 2002; Mottard & Fissore, 2007; Roux et al., 2004; Voeltzel et al., 2001; Wall, 1995)

Table 1: Overview of some studies into courtyard, atrium and sunspace buildings.

Several studies (table 1) have shown the environmental advantages of transitional spaces. Future lack of fossil energy and the limited capacity of sustainable energy sources encourage us to investigate passive and efficient building forms; like courtyards or atria. Moreover, there is still a lack of knowledge on the effect of transitional spaces on the energy consumption of and thermal comfort in residential buildings, since most studies addressed office buildings.

This paper therefore presents the results of a preliminary study into the influence of transitional spaces in dwellings concerning energy performance and thermal comfort. Four building types – a reference dwelling, a dwelling with a courtyard, a dwelling with an atrium and a dwelling with a sunspace – are simulated with DesignBuilder having EnergyPlus as its simulation engine. Three different climates were selected for the simulations. In the section on energy consumption, the paper compares the four building types in the context of these three climates. Furthermore, the paper elaborates the thermal comfort situation of dwellings specifically for the climate of the Netherlands. With these results the following question will be answered: to what extent can certain transitional spaces reduce the energy consumption of and improve thermal comfort in houses?

2. Method: Energy modelling using EnergyPlus (DesignBuilder)

This research uses DesignBuilder which is based on the state-of-the-art building performance simulation engine EnergyPlus. The simulation principle used by DesignBuilder is the most detailed simulation with dynamic parameters and they include all energy supply and energy dispersion. Moreover, EnergyPlus uses a modular programme structure, which makes the different calculation methods easy to understand. The simulation is based on hourly weather data from the US Department of Energy and takes among others into account solar heat gains through windows, heat conduction and convection between different zones and the energy applied or extracted by mechanical systems (Chowdhury et al., 2008; DesignBuilder, 2009). Moreover, DesignBuilder is validated through the BESTest (Building Energy Simulation TEST) procedure, developed under auspices of the International Energy Agency.

For this study, the following are implemented in DesignBuilder:

a) Construction:

In the simulations, the wall and roof types are defined by the authors.

- The external walls have 5 layers: brickwork (10 cm), air cavity (4 cm), EPS (expanded polystyrene) as thermal insulation layer (10 cm), concrete blocks

(10 cm), and gypsum plastering (1 cm), respectively from outer surface to the inner one. The *U*-value of this wall section will be 0.312 W/(m^2K) in total.

- The external roof of the building is also made from 5 layers, from outside to inside: bitumen (3 mm), fibre board (1.3 cm), XPS extruded polystyrene as an insulation layer (8 cm), cast concrete (10 cm), and finally gypsum plastering 1.5 cm. the *U* value of the roof is 0.326 W/(m^2K).

b) Openings:

The percentage of window to wall is maintained at 30% for all models. Moreover, the type of glazing is double glazing with 2 layers of 3mm clear float glass and 13 mm of air within those. The *U*-value of this glazing type is 1.96 W/m^2K. The courtyard building has 30% of glazing in the courtyard facades. The atrium also has this window to wall ratio for the internal windows. The roof of the atrium has two layers of 3 millimetre glass. The top roof of the sunspace is identical to the roof of the atrium; however, the internal walls are 100 percent glazed.

c) HVAC:

The HVAC system is based on mechanical ventilation with heat recovery and natural ventilation in summer in case of overheating. The heating set point is 21^{o} Celsius and the heating set back is 12^{o}C. Moreover, natural ventilation only operates when the indoor temperature has risen to above 22^{o}C. To add up, the heating system is based on radiators with hot water heated by a gas boiler.

d) Climatic data:

In these simulations, three different climates based on the Koppen and Geiger climate classification were tested (Kottek et al., 2006): temperate, hot-arid and Mediterranean. On this account, we selected weather data from three representative cities: Rotterdam (55°N, 4°E in the Netherlands), Cairo (30°N, 31°E in Egypt), and Barcelona (41°N, 2°E in Spain).

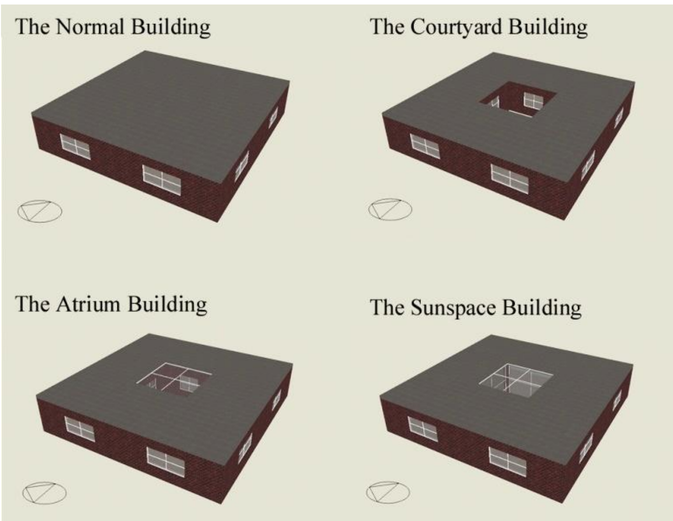

Figure 1: The visualised four models for the simulation.

e) Dwelling shape and size:

The dwellings modelled are rectangular with a size of 15 x 15 meter. The empty space for the courtyard, atrium or sunspace is 5 x 5 meter centred in the middle. The dwellings are one storey high and consist of just one thermal zone.

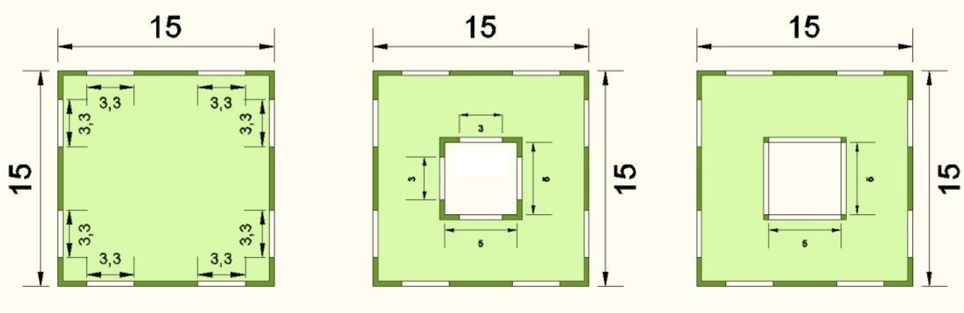

Figure 2: Left: The floor plan of the reference building; Middle: The floor plan of the courtyard and the atrium; Right: the floor plan of the sunspace.

3. Thermal comfort standards

Several ways of assessing thermal comfort exist. The ASHRAE method, the adaptive comfort algorithms and the adaptive temperature limits model will be described.

1. ASHRAE

In the 1990s, ASHRAE commissioned deDear and Brager (1997) to conduct a specific research project to collect information from a lot of different field studies performed in countries like Thailand, UK, Indonesia, USA, Canada, Greece, Pakistan and Singapore. The total amount of 22,346 data points were later concluded to the following equations:

$$T_{CO} = 0{,}31 \cdot T_{ext,ref} + 17{,}8$$

in case of naturally ventilated buildings and for outdoor temperatures ranging from 5°C to 32°C, and to

$$T_{CO} = 0{,}11 \cdot T_{ext,ref} + 21{,}45$$

in case of 'HVAC buildings'. In this case $T_{ext,ref}$ is the monthly average outdoor temperature.

It is clear that the 'adaptiveness' (represented by the slope value) is much higher in case of unconditioned buildings. The research found two acceptability ranges, which correspond to percentages of satisfied occupants and which are defined by constant values: an 80% acceptability range connected to a temperature interval of 3.5°C for typical application and a 90% acceptability range connected to a temperature interval of 2.5°C in case a higher level of thermal comfort may be desired. The first equation resulting from this study was later implemented in the American Standard regarding the assessment of the thermal conditions in indoor environments (ASHRAE, 2004), with the following limitations:

- for the summer season, in particular for $T_{ext,ref}$ ranging between 10 °C and 33.5 °C;
- in case of buildings where occupants can directly operate windows;
- in case of buildings where the occupants perform low metabolic rate activity (<1.3 MET).

2. EN 15251- Adaptive Comfort Algorithms (ACA)

The Smart Control and Thermal Comfort project (SCAT), promoted by the European Commission, aimed to reduce energy use due to air conditioning systems by varying the indoor temperature through the use of an "adaptive algorithm" (McCartney & Nicol, 2002). In this study, 26 European office buildings in France, Greece, Portugal, Sweden and the UK were surveyed covering several specific functions and HVAC systems (naturally ventilated buildings, climatised buildings and mixed-mode buildings). From the different national results, a general European equation, as well as equations for measured countries, called Adaptive Comfort Algorithms (ACA), were developed:

Country	**Adaptive Control Algorithm**	
	$T_{rm} \leq 10°C$	$T_{rm} > 10°C$
All	22.88°C	$0.302 \cdot T_{rm} + 19.39$
France	$0.049 \cdot T_{rm} + 22.58$	$0.206 \cdot T_{rm} + 21.42$
Greece	NA	$0.205 \cdot T_{rm} + 21.69$
Portugal	$0.381 \cdot T_{rm} + 18.12$	$0.381 \cdot T_{rm} + 18.12$
Sweden	$0.051 \cdot T_{rm} + 22.83$	$0.051 \cdot T_{rm} + 22.83$
UK	$0.104 \cdot T_{rm} + 22.58$	$0.168 \cdot T_{rm} + 21.63$

Table 2: Adaptive Comfort Algorithms for individual countries (McCartney & Nicol, 2002).

where T_{rm} is the running mean temperature calculated for a suggested time interval of 3.5 days. This equation is considered reliable only for outdoor temperatures higher than 10 °C, while below this limit a constant value of T_{co} = 22.88 °C has to be considered.

3. ATG

In the Netherlands, the findings of deDear and Brager (2002) were used to develop the local standard regarding adaptive comfort, called Adaptive Temperature Limit (ATG) (van der Linden et al., 2006). In this case, the outdoor reference temperature is determined by the running mean temperature, from:

$$T_{rm} = \frac{T_i + 0.8 \cdot T_{i-1} + 0.4 \cdot T_{i-2} + 0.2 \cdot T_{i-3}}{2.4}$$

This equation is based on a time interval of 4 days back in time starting from the current one: the use of ATG is limited to analyses during the design phase, through building simulation, and/or during the operation phase, through data registered in the field.

In this approach, buildings are divided into two categories (type Alpha and type Beta) which differ by the accorded ‘adaptive opportunity’ (mostly meaning the accessibility of environmental controls, operating both windows and HVAC system). A flowchart is provided together with the standard to distinguish between the two building categories: this sorting tool is being assessed and is likely to be adjusted according to the lessons learnt by its practical application. Even if it is not definitive, this approach is very interesting, because it attempts to avoid the ambiguities connected to the traditional distinction between naturally ventilated and HVAC buildings without underestimating the occupants’ adaptation potential (Ferrari & Zanotto, 2012).

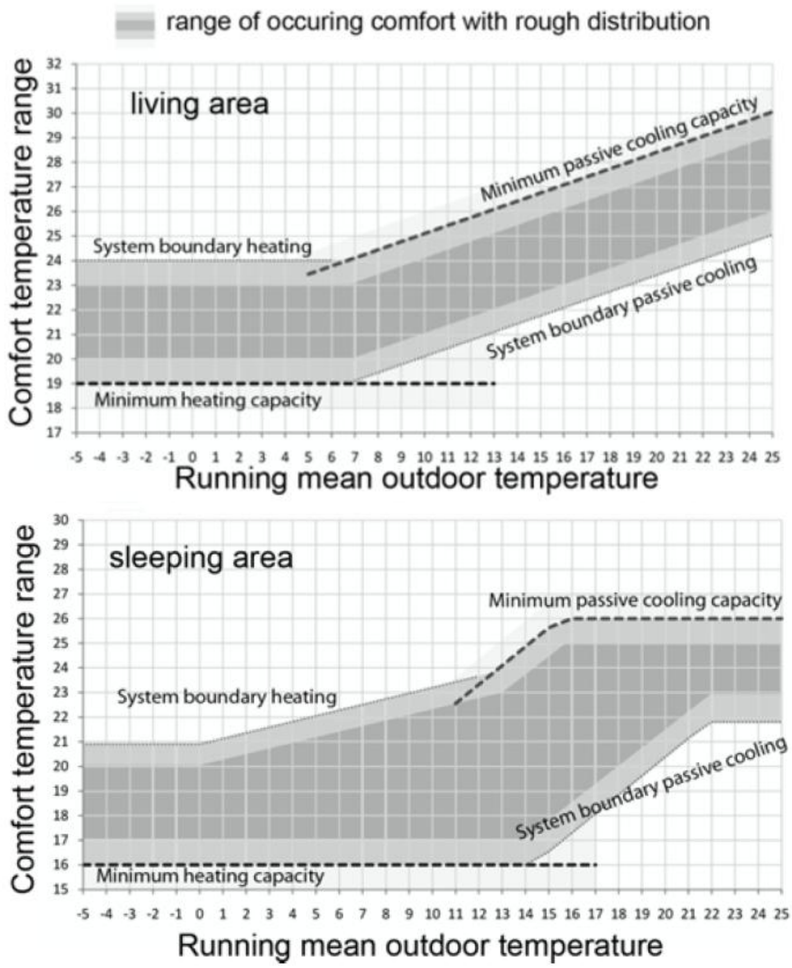

Figure 3: Adaptive bandwidths for space temperatures for living areas (left), and bedrooms (right) as a function of the prevailing outdoor temperature (running mean outdoor temperature) according to the ATG (Alders et al., 2011).

Figure 3 depicts comfort bandwidths for the living room of residential spaces adopted for the Netherlands (Alders, et al., 2011). This graph is derived from a Belgian study (Peeters et al., 2009). This Belgian study is consecutively based on a study done for office buildings in the Netherlands (van der Linden, et al., 2006), which used ASHRAE efforts (ASHRAE, 2004). Table 3, finally, presents an overview of the development through time of comfort charts used in this research:

Standard	Description of comfort temperature calculation and range for 10-20% acceptability
PMV-PPD ISO 7730	T_{comf} is 22°C in winter and 24°C in summer. Summer days are defined by a daily maximum temperature of 25°C. A total of 90% and 80% of people satisfied are calculated using the PPD model, but come at approximately T_{comf} ± 2.5 and 3.5°C, respectively.
ASHRAE 55	Derived from a global comfort database, T_{comf} is 22°C in winter and 17.8°C + 0.31 × T_m in summer, where T_m is the monthly average of the daily average outdoor dry bulb temperatures. A total of 90% and 80% of people satisfied are assumed to fall at T_{comf} ± 2.5 and 3.5°C, respectively.
EN 15251	Derived from a European comfort database, T_{comf} is 18.8°C + 0.33 × T_{rm7} in summer, where T_{rm7} is the exponentially weighted running mean of the daily outdoor temperature, approximated using the previous week's temperatures as: $T_{rm7} = (T_{-1} + 0.8T_{-2} + 0.6T_{-3} + 0.5T_{-4} + 0.4T_{-5} + 0.3T_{-6} + 0.2T_{-7})/3.8$, where T_{-n} is the average outdoor temperature n days before the day in question. A total of 90% and 80% of people satisfied are assumed to fall at T_{comf} ± 2.0 and 3.0°C, respectively.
NPR- CR 1752	Dutch code of practice. T_{comf} is 17.8°C + 0.31 ×T_{rm3} for type 'beta' buildings in cooling mode, where T_{rm3} is calculated from the averages of the maximum and minimum outdoor temperature of the day under study and the three preceding days as: $T_{rm3}= (T0 + 0.8T_{-2} + 0.4T_{-3} + 0.2T_{-4})/2.4$, where T_{-n} is the average outdoor temperature n days before the day in question. A total of 90% and 80% of people are assumed to be not uncomfortably hot at T_{comf} ±2.5 and 3.5°C, respectively (there is a separate calculation for the lower bounds of comfort).

Table 3: Details of comfort temperature calculations for all four comfort models: summary of T_{comf} (also known as comfort temperature or neutral operative temperature where the lowest total percentage of people are expected to be either too hot nor too cold) calculations with 90% and 80% of people-satisfied thresholds from the various standards examined in this study (Borgeson & Brager, 2011).

4. Energy performance: comparison of the results in different climates

For the first step of this study, the mentioned models in the three cities were simulated. The results are described as a figure for each city. In section 6, a comparison between all climates and results is made:

4.1. Rotterdam

In the temperate climate of the Netherlands, cold winters cause large heat losses through the walls of the courtyard. In this case, the courtyard annually needs 16kWh/m^2/yr for heating more than a cubic reference model needs. Moreover, its annual heat loss is 34 kWh/m^2/yr more than the reference model. On the other hand, the annual solar gains through the windows are 23 kWh/m^2/yr more. This shows the courtyard has the potential to absorb more sun. Whenever we cover the courtyard to create an atrium, the heat loss is reduced with 26 kWh/m^2/yr. Furthermore, when the atrium is converted to a sunspace (with 100% glazed walls), the solar gains and heat losses increase. However, the energy consumed for cooling is also increased due to overheating inside the sunspace.

In these models, although heat losses are more than the reference model, they achieve more solar gains through their windows which can be used to compensate the heat losses. To add up, the courtyard has the highest energy consumption, highest solar gains and highest heat losses. This shows the importance of heat exchange through the external envelops in this climate.

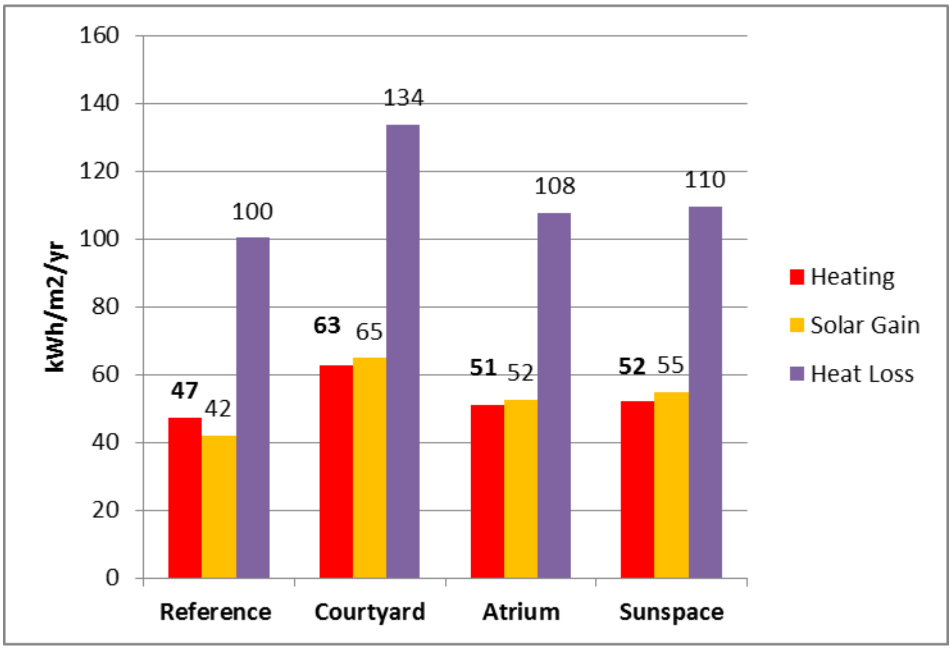

Figure 4: Energy demand for heating and cooling, solar gains through windows and heat losses of models in the temperate climate of Rotterdam.

4.2. Cairo:

In the hot arid climate of Cairo, indoor environments have a high risk of overheating. In other words, the more glazing, the larger the probability of overheating is. Therefore, atrium and sunspace buildings bring overheating if they have a fixed roof. This always causes more energy usage for cooling than the reference model (21 and 32 kWh/m^2/yr respectively). Moreover, based on figure 5, the courtyard receives more solar gains (14 kWh/m^2/yr) but needs less energy for cooling (4 kWh/m^2/yr) than the atrium. This shows the potential of natural ventilation in the open space of the courtyard for reducing energy demand for cooling in Cairo. In addition, solar gains in the sunspace and the courtyard dwellings are equal, while the cooling energy demand for the sunspace is much higher (15 kWh/m^2/yr). Consequently, providing closed glazed spaces with no ventilation increases overheating and leads to more cooling demand.

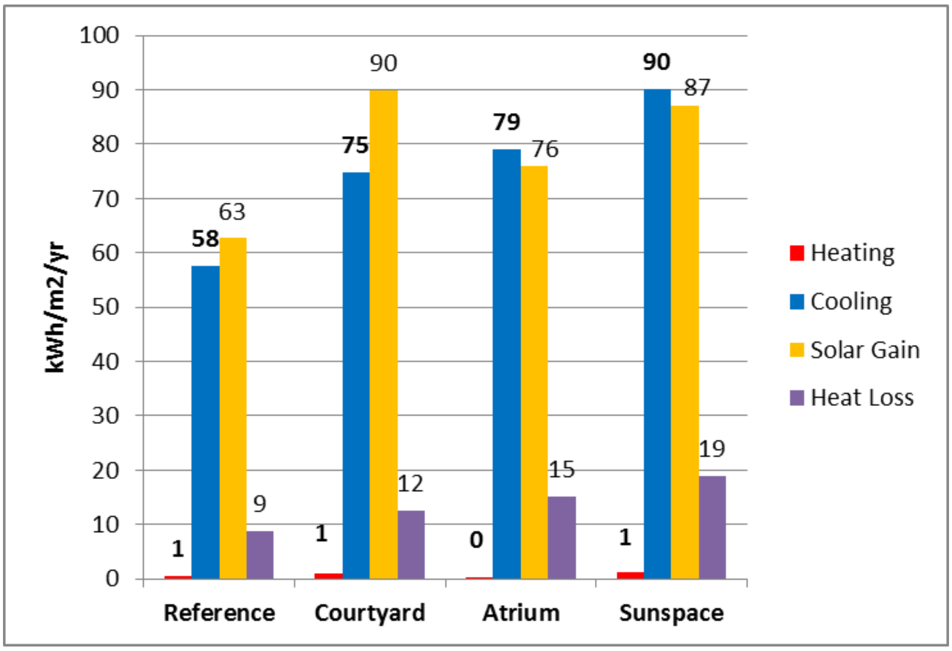

Figure 5: Energy demand for heating and cooling, solar gains through windows and heat losses of models in the hot arid climate of Cairo.

4.3. Barcelona:

In the case of Barcelona, the courtyard has the highest solar gains (82 kWh/m^2/yr) among the dwelling types. Moreover the heat losses are much more than in case of the other models because of its larger exposed surface area. On the other hand, the atrium with less solar gains (than the courtyard), consumes double the amount of energy for cooling (27 kWh/m^2/yr). This amount is even higher for the sunspace dwelling which receives more sun due to larger windows around the courtyard. The results are similar to those for Cairo: the building should be protected from sun while there is always need for ventilation or cooling to prevent overheating.

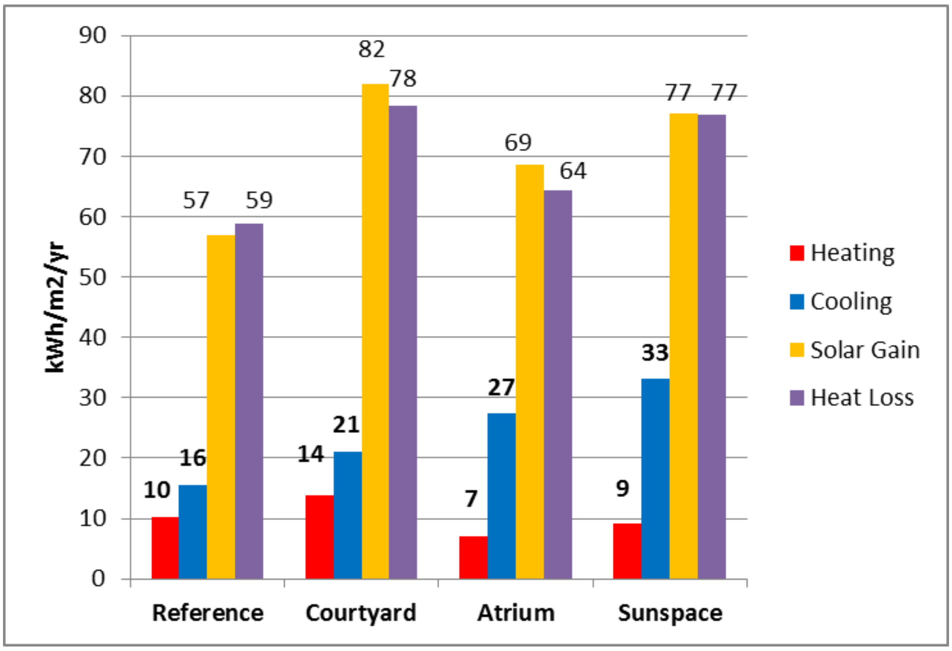

Figure 6: Energy demand for heating and cooling, solar gain through windows and heat loss of models in the Mediterranean climate of Barcelona.

5. Comfort situation in the case of Rotterdam

In this section, thermal comfort in the four buildings simulated in the Netherlands is compared. In the previous section, we saw that the reference model, the courtyard, the atrium and the sunspace model consume 47, 63, 51 and 52 kWh/m^2/yr of energy (respectively). Figure 7 shows the situation of comfort hours in the four simulated building types in the Netherlands.

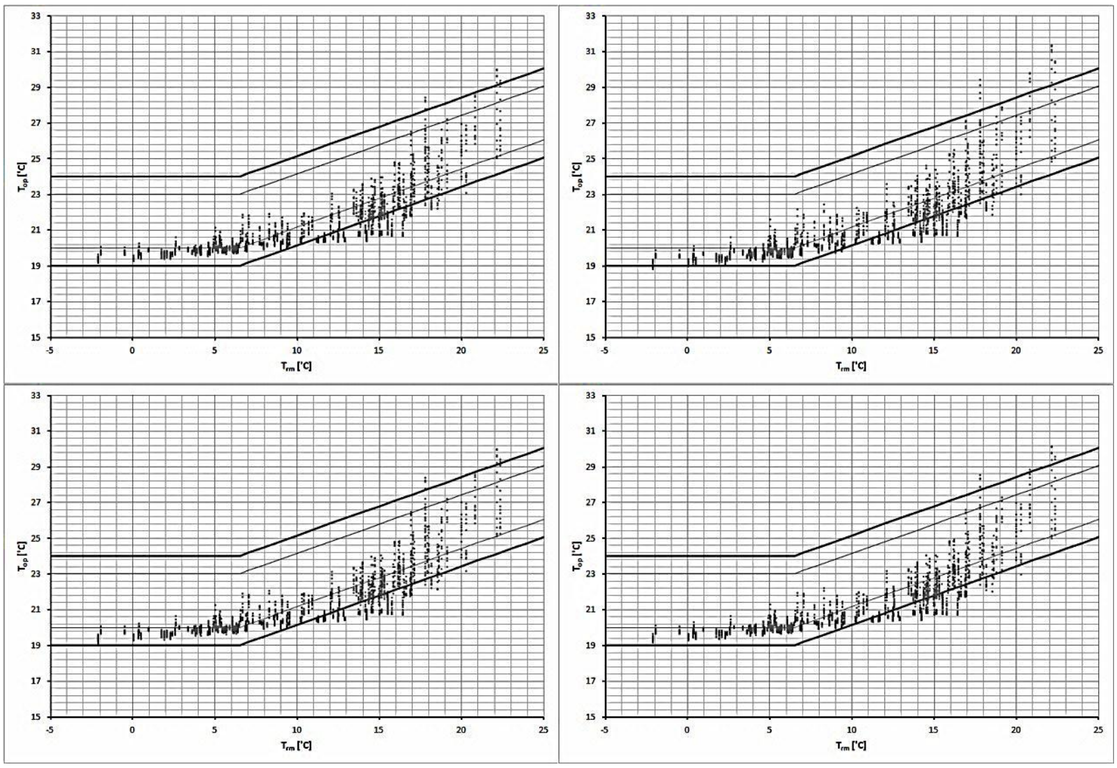

Figure 7: Hourly data of the operative temperature as function of the running mean temperature for the Netherlands in the reference dwelling (top left); courtyard dwelling (top right); atrium dwelling (down left); and sunspace dwelling (down right).

Based on figure 7, in the case of Rotterdam, the comfort hours for the models are 82% for the reference model, 81.6 % for the courtyard, 83.2% for the atrium model, and 82.3% for the sunspace.

In this section, authors tried to simulate a flexible model between the courtyard and the atrium for the climate of Rotterdam. This new model is an atrium which has no glazed roof for the durations of:

a) three months (Jun, July, August),
b) four months (Jun, July, August, September),
c) five months (May, Jun, July, August, September), and
d) six months (April, May, Jun, July, August, September).

This means that during the mentioned months, the model can use natural ventilation from the open courtyard and is protected during the cold months. In figure 8 and table 4, it is possible to review the results of this new model for the amount of energy consumed and the comfort situations.

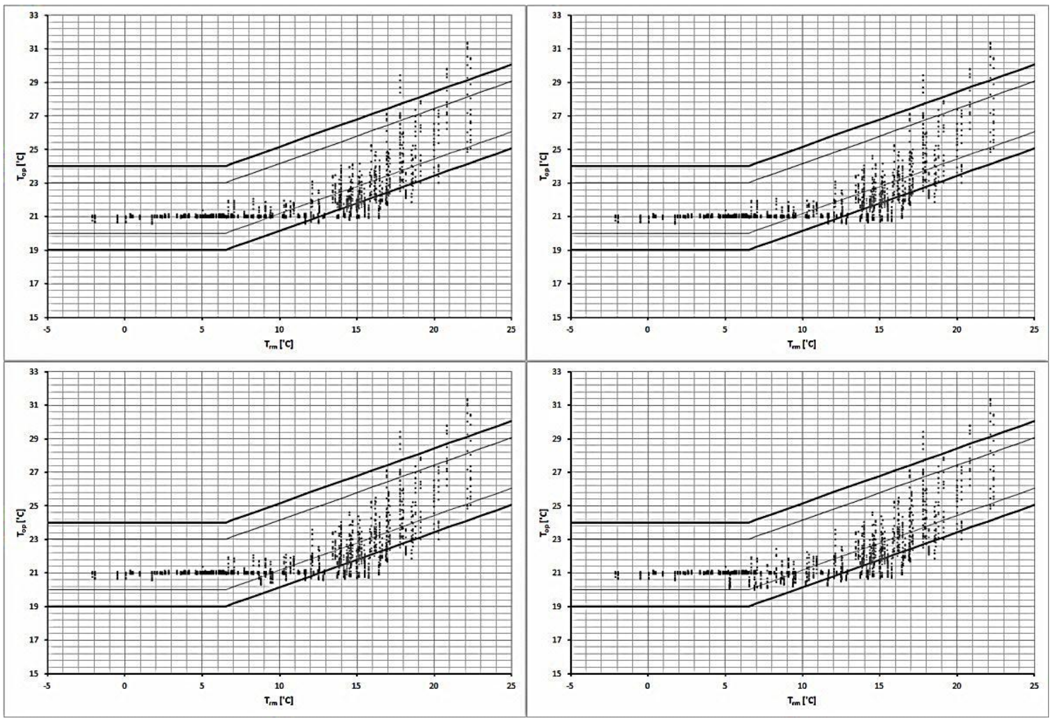

Figure 8: The comfort situation in the new atrium which has no roof for the mentioned three months (top left); four months (top right); five months (down left); and six months (down right).

Removed roof during	Heating (kWh/yr)	Comfort hours (%)
Jun, Jul, Aug	9222	84.8%
Jun, Jul, Aug, Sep	9255	85.2%
May, Jun, Jul, Aug, Sep	9295	85.7%
Apr, May, Jun, Jul, Aug, Sep	9405	84.8%

Table 4: the energy consumption versus comfort situation in the new atrium model.

Based on table 4, it is clear that by removing the glazed roof of the atrium during some months, it is possible to change the energy demand for cooling, and the comfort situation. The results show the highest percentage of comfort hours during the five months of May till September. In addition, when we add April to the duration which the atrium is open to the sky, the heating demand starts to increase while the percentage of comfort hours decreases 1%. This one percent means 125 hours of the occupation time will be not-comfortable.

6. Discussion: Comparison of the results in different climates

6.1. Rotterdam

The dwelling types in different climates have different results. In the temperate climate of Rotterdam, a courtyard with 80% of surface to volume ratio has lots of heat losses during winter. This building type is not recommended for this climate. likewise, the atrium and the sunspace have more energy demand for heating than the reference model since they have less protection from the outdoor environment (because of a glazed roof on top of the open space). Considering thermal comfort, the atrium has the highest comfort hours among the models (83.2%). This percentage means that the atrium has 150 hours more comfortable than the reference model (in a year). In this regard, the courtyard has the lowest efficiency. This model has the highest energy demand while it has the lowest comfort percentage.

Location	Heating+Cooling Energy Use		Comfort hours (%)	Mean Indoor Air Temp °C
	kWh/yr	kWh/m^2/yr		
Rotterdam:				
Reference	9666	47	82	22.6
Courtyard	10771	63	81.6	22.6
Atrium	9137	51	83.2	22.7
Sun Space	9218	52	82.3	22.7
Cairo:				
Reference	11910	58	-	23.9
Courtyard	13048	76	-	23.9
Atrium	14242	79	-	24.2
Sun Space	16422	92	-	24.1
Barcelona:				
Reference	5275	26	-	22.7
Courtyard	6020	35	-	22.6
Atrium	6176	34	-	22.9
Sun Space	7574	42	-	22.8

Table 5: comparison of energy consumption of the reference, the courtyard, atrium the atrium and the sunspace model in the three cities.

6.2. Cairo

In Cairo, there are no significant differences between energy demand for heating among the models. The reference model is the most efficient one since it is protected from the sun. The other models consume large amount of energy for cooling. Therefore, the energy used for cooling can be a good criterion to choose among the models. The sunspace becomes a greenhouse needing lots of energy for cooling to maintain acceptable indoor temperatures. Therefore, among the transitional spaces, the courtyard is the most efficient. This building type can also be combined with passive solutions for cooling or sun-shading (like trees and shrubs) to reduce overheating.

6.3. Barcelona

In case of Barcelona, the reference model has the lowest energy consumption (26 kWh/m^2/yr) for heating and cooling. However, among transitional spaces, the atrium seems to be the most efficient model. Furthermore, the standard deviation of indoor air temperature for the atrium and the sunspace is the highest while the courtyard and reference model have a more stable indoor air temperature.

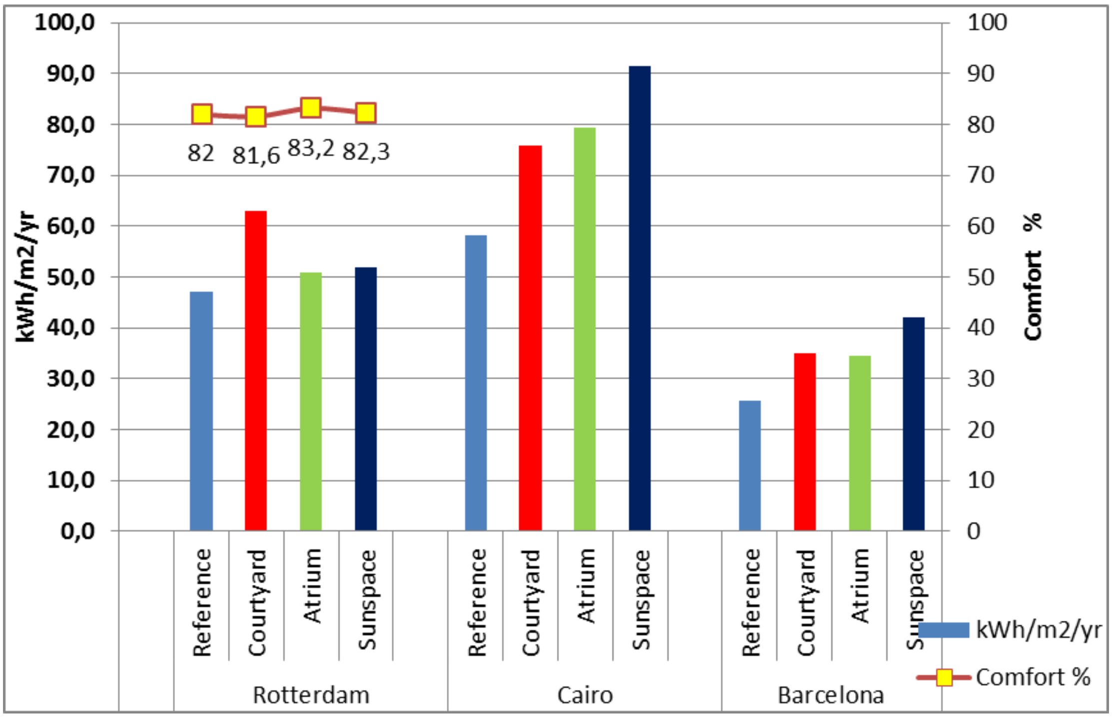

Figure 9: Total energy consumption for heating and cooling in comparison with comfort situation of different types of dwellings in the context of three climates (sum of 12 months).

Conclusion and discussion

This paper discussed thermal comfort in and energy consumption of dwellings with transitional spaces. In this regard, the paper first compared heating and cooling energy consumption of a reference dwelling (with no transitional spaces) with a courtyard dwelling, an atrium dwelling and a sunspace dwelling in a temperate, a hot-arid and a Mediterranean climate. The paper showed that the reference building has in all climates the lowest energy consumption of all the dwellings studied. Second, the comfort hours of the mentioned cases were examined for Rotterdam. This case showed that the most energy-efficient building does not always have the most comfort hours. The results showed atrium and sunspace dwellings have a good situation of comfort in the temperate climate of the Netherlands (in comparison with their annual energy consumptions). To add up, the findings presented in this paper suggest that courtyard dwellings are not recommended for the climate of Rotterdam. In this regard, the sunspace does not show to be efficient building type in the hotter climates of Cairo and Barcelona.

The study however only focused on energy used for heating and cooling. Since courtyard, atrium and sunspace building types provide a high daylight factor, further research will be conducted to also consider lighting energy. That research may show whether or not these transitional spaces are suited for these climates; for instance for buildings with daily activities such as education, health care or office work. Moreover, our study only involved crudely designed courtyards, atria and sunspaces. Proper parametric design of details – for example regarding the roof's edge, adjustable sun shading, different solutions for north-, east-, west- and south-oriented inner facades and higher buildings – could produce different results. Further research will clarify this.

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