Positioning of outdoor space in house design - an energy efficiency and thermal comfort perspective

Positioning of Outdoor Space in House Design – An Energy Efficiency and Thermal Comfort Perspective

by

Masoud Malekzadeh

A doctoral thesis
presented to Loughborough University
in fulfilment of the
requirement for the degree of
Doctor of Philosophy

Loughborough, Leicestershire, United Kingdom, 2009

Borrower's Page

Loughborough University requires the signatures of all persons using or photocopying this thesis. Please sign below, and give address and date.

Abstract

The present thesis is primarily motivated by the will to provide help for decision-making on the overall layout of a house or a housing development in the very early stages of design from the point of view of energy efficiency and thermal comfort. This study contributes towards a deeper understanding of thermal interactions between a house and its adjacent enclosed open spaces. It addresses the contribution of the yard design, i.e. placement, size and type towards the development of a comfortable microclimate within the yard itself, as well as the reduction of total energy demands of the house for mechanical heating and cooling. The focus is put on the applicability of the results and findings are expressed in form of a decision-making aid.

This research also makes empirical and analytical assessments on the validity of some existing methods and tools that are used for understanding the nature of microclimates in small scales and proposes methods for their improvement, particularly when used in conjunction with standard tools for the assessment of indoor climates. These methods are also demonstrated through an exemplary application in an archetypal setting and the results of the exemplary case are analysed to reach a decision on the most advisable design layouts for the buildings in the example.

As a result, this work emphasises on the importance of private outdoor spaces and how their careful design can benefit occupiers, investors and the environment.

Keywords: simulation, outdoor thermal comfort, energy consumption, house/yard configuration, courtyard, Iran, Isfahan

List of Contents

List of figures

List of tables

List of symbols

Symbol	Typical unit	Description	Derived from /or value
ASV	-	Actual sensation vote	scale from -2 to +2
A_w	m^2	surface of the wall	
D_i	W/m^2	diffuse and diffusely reflected short-wave radiation component	
E_i	W/m^2	long-wave radiation component	$\sigma_B\ \varepsilon_i\ T_i^4$
F	$mm\ Hg$	saturation vapour pressure at 36.5 $°C$	45.4 mm Hg
f	$mm\ Hg$	vapour pressure of the air	
F_{fs}	-	Sky view factor for the floor	
F_{fw}	-	Wall view factor for the floor	
F_i	-	angle weighting factor	
f_p	-	surface projection factor	
F_{wf}	-	floor view factor for the enclosure wall	
F_{ws}	-	sky view factor for the enclosure wall	
H	$mCal / cm^2 \cdot S$	dry cooling power of the atmosphere	
H	$Kcal / m^2 hr$	heat loss of the body	
H'	$mCal / cm^2 \cdot S$	wet cooling power of the atmosphere	
h_c	$W/m^2 °C$	convective coefficient of the wall	
I	W/m^2	direct solar radiation impinging normal to the surface	
J_f	W	total radiative energy leaving the floor surface per unit area	
J_s	W	total radiative energy leaving the sky surface per unit area	
J_w	W	total radiative energy leaving the wall surface per unit area	
J_λ	W	hemispherical spectral radiosity	

Symbol	Typical unit	Description	Derived from /or value
k	-	Proportion of metabolic heat dissipated by means other than evaporation	≈0.8
K_h	-	diffusion coefficients for heat	
K_i	W/m^2	short-wave heat flux	
K_q	-	diffusion coefficients for vapour	
L_i	W/m^2	long-wave heat flux	
M	W	metabolic rate	
M_{Du}	W/m^2	Metabolic rate of heat production per square metre of body surface	
P	-	perception of climate	scaled from 1 to 7
Q	W	net radiation balance of the body	
Q_{cond}	W	heat loss through the conduction in the wall	
Q_{conv}	W	heat loss from the surface of the wall to the outdoor air through convection	
Q_H	W	convective heat flow (sensible)	
Q_h	-	heat exchange rate between the foliage surface and the surrounding air	
Q_L	W	latent heat flow for diffusion of water vapour	
Q_q	-	vapour exchange rate between the foliage surface and the surrounding air	
Q_R	W	net amount of heat radiated by the wall surface to other surrounding surfaces	
Q_{RE}	W	respiratory heat flux	sum of heat flow for heating and humidifying the inspired air
Q_{SW}	W	latent heat flow due to evaporation of sweat	

Symbol	Typical unit	Description	Derived from /or value
R_b	$m^2.°C/W$	Thermal resistance of body tissues	ranging from 0.04 to 0.09 $m^2.°C/W$
R_c	$m^2.°C/W$	Thermal resistance of clothing	
RH	%	relative humidity	
RH'	%	Relative humidity at the meteorological station	
R_w	m^2K/W	thermal resistance of the wall	
S	W	storage heat flow for heating (positive value) or cooling (negative value) the body	
S	W/ m^2	Solar heat input per square metre of body surface	Max. ≈ 120 W/ m^2
S	W/m^2	solar radiation on land	
S'	W/m^2	Solar radiation at the meteorological station	
S_{rad}	W/m^2	mean radiation flux density	
T_a	°K	temperature of the layer of outside air next to the wall	
T_a	°C	ambient air temperature	
T_b	°C	Body core temperature	37 °C
T_c	°C	comfort temperature	
T_f	°K	Floor temperature	
T_{g-a}	°C	Difference between globe temperature and air temperature	T_g-T_a
T_i	°K	Air temperature in the room adjacent to the courtyard	
T_{mrt}	°C	mean radiant temperature	
T_o	°C	outdoor air temperature	
T_r	°K	inner surface temperature of the wall	

Symbol	Typical unit	Description	Derived from /or value
T_s	°K	Sky temperature	
T_s	°K	surface temperature on the outer surface of the wall surrounding the courtyard	
T_w	°K	surface temperature of the wall on the outer surface	
T_w	°K	temperature of the outer surface of the wall facing the courtyard	
T_y	°K	Air temperature in the courtyard	
v	m/s	air velocity	
v'	m/s	Wind speed at the meteorological station	
W	W	physical work output	
W_i	-	related angle factor	percentage of the hemisphere taken up by each part of the body in each direction
a_k	-	absorption coefficient of the irradiated body surface for short-wave radiation	≈ 0.7
ε_f	-	Emissivity of the floor	
$\acute{\varepsilon}_f$	-	-	$1 - \varepsilon_f$
ε_p	-	emissivity of the human body	≈ 0.97
ε_s	-	Emissivity of the sky	1
ε_w	-	Emissivity of the surrounding wall	
$\acute{\varepsilon}_w$	-	-	$1 - \varepsilon_w$
σ	W/m^2K^4	Stefan-Boltzmann constant	$5.67 \cdot 10^{-8}\ Wm^{-2}K^{-4}$
τ_f	°K^4	-	$\sigma T_f^4 \varepsilon_f$
τ_w	°K^4	-	$\sigma T_w^4 \varepsilon_w$

1. Introduction

1.1 Necessity of the study

"*Pairi daêza*" is an Old Persian term, meaning a garden enclosed with walls. From this origin are the words *"pardis"* in Modern Persian, *"paradis"* in Old French, *"paradisus"* in Late Latin, *"paradeisos"* in Greek, *"firdaus"* in Arabic and *"paradise"* in English (Skeat 2007).

Figure 1.1 Paradise; A garden enclosed with walls (researcher's personal collection)

A private Eden garden has deep roots in Iranian art and culture. An Iranian mind's obsession with combining wall and garden, brick and flower, mass and space, man-made and natural and private and open has resulted in a phenomenon called "the Iranian courtyard". An Iranian courtyard is more than just a garden that is used for growing vegetables and flowers. It is more like one of the rooms of the house. In fact, it is the biggest, the most central, the most public and, therefore, the most important room of the house. It is the only place in the house that none of the family members need anybody else's permission to enter and, for that reason, it is the most frequently used part of the house and the centre of the family life. It is where, when weather permits, most of the family activities take place, activities such as family gathering, dining, entertaining guests, praying and sleeping.

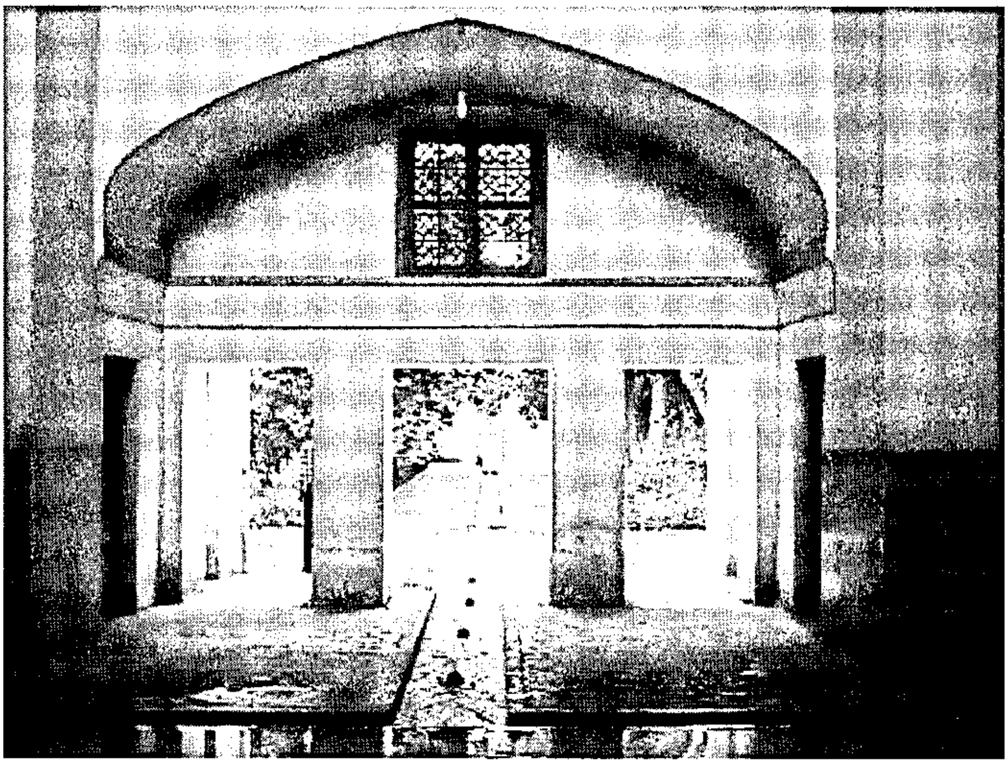


Figure 1.2 Fin mansion, Kashan, Isfahan province, Iran (Personal collection)

Central courtyards have been the focal point of the Iranian house design for centuries (Pope 1982). Courtyard houses have comprised the dominant majority of all houses in Iranian cities and in many rural parts (Memarian 1998). It was only in the twentieth century that some other alternative designs started to gain popularity. The new generation of Iranian architects, the graduates of European schools of art and engineering, introduced new fashionable designs that were faster and cheaper to build and easier to host the modern age needs and lifestyle (Heydari 2000). With the help of Governmental legislations and investments, this modern fashion grew very quickly and took over most of the cities in Iran in less than 50 years. The fast growing oil industry and the fascinating idea of complete four season comfort in the modern houses sounded convincing enough to Iranians to convert each central courtyard house to a multi-storey complex of flats. (Malekzadeh 2002)

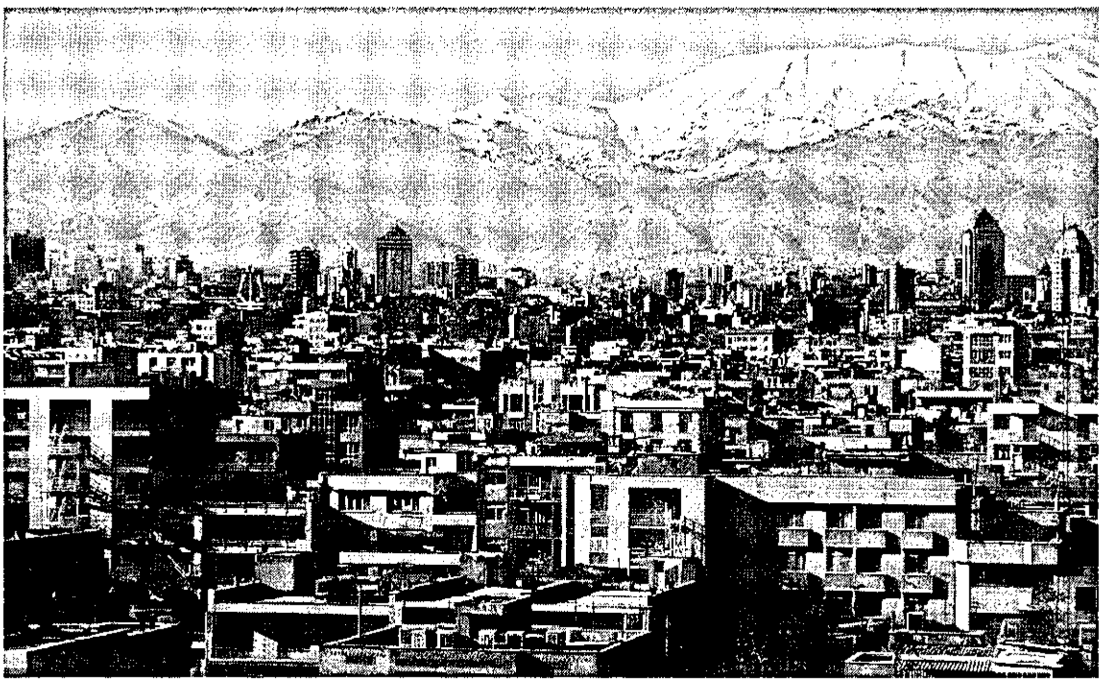


Figure 1.3 Modern Tehran, Iran (personal collection)

The simultaneous occurrence of an economic crisis (energy crisis) and a cultural one (postmodern movement) in the 1970s society of Iran made policymakers, designers and the public reconsider their fascination with this lifestyle. The Energy crisis, although provided the country with a vast amount of money in a very short time, led to an increasingly faster draining of oil resources and the general worry of the exhaustion of these reserves. Postmodernism, on the other hand, triggered the reminiscence of a serene, beautiful and comfortable living environment in historical traditions of architecture.

Ever since then, the discussion of choosing one of these two trends (traditional central courtyard or modern western-style, with 'yard) against the other has been going on among Iranian designers. Some have looked at this matter from a cultural perspective, some from an economic one and others from social, political, aesthetical et cetera. One of the important aspects of this discussion has always been the matter of energy efficiency and thermal comfort. Some have claimed that central courtyard houses are more energy efficient and their open spaces (courtyards) are more thermally comfortable compared to block houses of similar size and construction (Heydari 2000). Some accept the higher thermal comfort sensed within the courtyards but argue that this comfort is not worth the extra money spent on heating and cooling of central designs (Abulqasemi 1995). A third group divide the issue into two parts (the placement of the courtyard and its interior design) and discuss that there is no evidence that courtyards are more comfortable than other types of open spaces and that the higher thermal comfort normally associated with them is, in fact, due to the amount and the design of features like plants and water in the courtyards (Diba 1996).

Therefore, the question remains. Has the placement of the open space in a building got anything to do with the level of energy consumed in that building or the level of thermal comfort achieved within that open space? This thesis will try to find a general answer to this question using a quantitative approach and to suggest a method for finding a definitive answer to this question in any specific case.

Now and amidst a second and much bigger energy crisis (Figure 1.4), the importance of studies like this is becoming more and more obvious, especially considering that in the year 2007 more than 15% of this expensive energy was used for heating and cooling of residential buildings (US Department of Energy 2008).

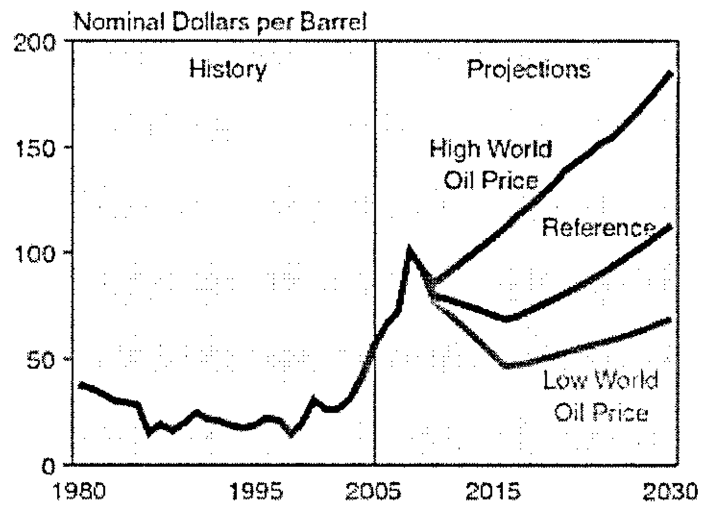


Figure 1.4 World oil prices 1980-2030 (DOE/EIA 2008)

1.2 Objectives of the study

The present work is primarily motivated by the will to provide help for decision-making on the overall layout of a house or a housing development in the very early stages of design from the point of view of energy efficiency and thermal comfort. This study seeks to contribute towards a deeper understanding of thermal interactions between a house and its adjacent enclosed open spaces. It addresses the contribution of the yard design, i.e. placement, size and type towards the development of a comfortable microclimate within the yard itself, as well as the reduction of total energy demands of the house for mechanical heating and cooling. The focus is put on the applicability of the results, i.e. expressed in form of a decision-making aid.

Using the proposed method, a set of archetypal house designs are then studied to demonstrate the application of this procedure in a real design process. The results of this study is presented in form of a ranking list of the design types most suitable for the defined problem (i.e. consumes the least amount of energy and offers the highest thermal comfort level).

A further objective of the work is to assess and validate the existing methods and tools used for understanding the nature of microclimates in small scales and propose methods for their improvement, particularly when used in conjunction with standard tools for the assessment of indoor climates. In order to validate these tools, an analytical model is designed and a series of field measurements are conducted. Comparing the results of these measurements and models against the values predicted by the tools under investigation will provide a clear understanding of the level of validity of these tools.

Furthermore, proposing a method for integrating indoor and outdoor simulation programs, which is an essential stage of the present research and all similar studies, is a further objective of this thesis.

Also a focus on gathering and presenting the existing knowledge on outdoor thermal comfort, as part of the metrics studied in this study, is essential.

As a result, this work intends to emphasise on the importance of private outdoor spaces and how their careful design can benefit occupiers, investors and the environment.

1.3 Methodology

The method used to achieve the objectives of the research is to establish a process of assessment for different available design types and then demonstrate its application through an example. The example will be based on the real weather data from a selected climate and will consist of all common combinations of house and yard in that climate. The combination types will be simplified and categorised into generic comparable archetypes and modelled and simulated under the weather data of a whole year in order to give an indication of the level of energy consumption and thermal comfort in each type. The results will be presented in the form of a ranking list of the priorities that could be advised to the decision-makers.

Therefore, the present research is mainly carried out by using a numerical methodology. The reason behind this choice is mainly its involvement with the outdoor comfort issue. One reason for the very limited number of field studies on outdoor thermal comfort is certainly the huge number of outdoor climatic variables and processes involved. This complexity makes it difficult to perform comprehensive field measurements and is probably the reason why most investigations concentrate on air temperature and humidity, which are much easier to measure. Indeed, it is costly to record continuously and for a large sample of outdoor environments all-wave radiation flux densities from the three dimensional surroundings of a human body, in addition to the commonly measured meteorological factors (i.e. air temperature, wind speed, and vapour pressure).

In this respect, numerical modelling, properly validated, has a distinct advantage over comprehensive field measurements and is, therefore, a powerful alternative for outdoor climate issues (e.g. Arnfield 1990a, Mills 1997, Capeluto and Shaviv 2001, Kristl and Krainer 2003, Bourbia and Awbi 2004, Asawa et al. 2004). In a review of the state of research development in urban climatology during the last two decades, Arnfield (2003) drew attention to the growing popularity of numerical simulation, described as a methodology perfectly suited to dealing with the complexities and non-linearities of urban climate systems.

Hence, the present research is mainly carried out by using a numerical methodology supported by validation, so that a series of geometries combined with various yard placements and other arrangements could be analysed and compared.

Simulation models vary substantially in many aspects: their physical basis, temporal and spatial resolution, input and output quantities, etc. (see Chapter 2). One of the tasks of this work will be to study, assess, select and validate two simulation programmes, one dealing with the thermal performance of the buildings and the other with the open spaces. Validation of numerical models is not an easy task, and as already noticed by Arnfield (2003), unfortunately, lags behind their creation and when performed, is often weak, relying more on plausibility of outputs than on direct comparison with process variables. According to the author, this is not surprising, because the difficulty of measuring such variables is a prime reason why numerical modelling is so popular, and a closer collaboration between modellers and field climatologists is encouraged to close the methodological gap (Ali-Toudert 2005). Therefore, an analytical model and the results of a short-term field measurement have also been conducted and are presented to allow further comparison and discussion.

Assessing comfort outdoors is not easy and methodological differences observed in the related literature make any comparison with available results difficult, and this will be discussed in the next chapter. Basically, comfort can be assessed by means of comfort indices. In this thesis available outdoor thermal comfort indices and their advantages and disadvantages will be discussed and one of them will be selected for the purpose of the study.

1.4 Structure of the thesis

Chapter 2 summarizes the most significant findings related to passive strategies to reduce energy consumption of a building and to achieve, assess and predict human comfort outdoors. Chapter 3 describes the physical processes which govern the model ENVI-met, a recently developed simulation tool for the outdoor environment, with a focus on the assessment of the validity of those of particular relevance in the framework of this research. The issues around linking the two main simulation tools of the study (ENVI-met and TRNSYS) are discussed comprehensively in Chapter 4. TRNSYS is a well-established simulation tool for modelling building thermal performance. In addition, an application of the method discussed in the previous chapter is introduced, modelled and simulated in Chapter 5 and the method for handling the simulation results is explained. A general discussion on the achievements and limitations of the research follows in Chapter 6. It includes a number of proposals for future studies in this field.

Remark: Symbols used in this work correspond to those commonly used in the international literature. Yet and for convenience of the reader, the nomenclature used to describe TRNSYS and ENVI-met is kept unchanged from the original source (TRNSYS 2008, Bruse 1999). Therefore, some physical quantities are referred to with more than one symbol or under more than one measurement unit system through this manuscript.

2. ■ Literature Review

2.1 Design strategies for reducing energy consumption

Before the advent of the industrial era and mechanisation, man depended on natural sources of energy and available local materials in forming his habitat according to his physiological needs. Over many centuries, people everywhere appear to have learned to interact with their climate. They built houses that were more or less satisfactory in providing them with the microclimate that they needed. This is what led many researchers to this fact that In consideration of climatic design the traditional houses have a lot of advantages (Rapaport 1969, Konya 1980). As Koenigsberger (1973) states, obviously not every traditional building is climate-sensitive, but there are some important lessons that can be learnt from studying them.

The importance of climatic consideration in housing design is clear, because a principal purpose of housing is to change the microclimate surrounding a person. In fact, the essence of climatic building design is that it recognises the role of the building as a mediator between the external climate as provided by nature, and the internal climate as required for the comfort of occupants (Baker 1987). Givoni (1994) notes that architectural means for achieving climatic design include such conventional design elements as the layout of buildings, orientation, size, location and detail of windows, shading devices, thermal resistance and heat capacity of its envelope.

In the hot arid zone of Iran, climatic consideration in traditional housing design has always been very important. There is no doubt that climate had its impact on a number of design and construction elements of traditional houses, such as internal circulation, external orientation and the use of materials and architectural elements.

In the past, people were forced to devise ways to cool their houses with only natural sources of energy and physical phenomena. It is, therefore, worthwhile to investigate these strategies in order to produce new strategies for the houses of today in response to questions such as the choice of a suitable site for houses, right direction, best shape, thermal capacity of materials and the choice of heating and cooling systems. Some of these strategies are here described.

When the outdoor temperature is higher than the indoor temperature, the roof and walls are exposed to the sun and are heated. They transmit this heat to the inner room surfaces, where it raises the temperature of the air in contact with room surfaces by convection. Heat is radiated and intercepted by people and objects indoors, thereby affecting thermal comfort. In hot countries it is popularly believed that the roof is the main heating element of a house followed by the walls (Givoni 1976).

On the other hand the thermal performance of roofs is closely associated with the issue of ceiling height. It is generally believed that high ceilings are more effective in providing cool interiors in buildings in hot dry areas than lower ceilings (Saini 1962). It is interesting that in the traditional houses in Iran, summer parts and the "Ivan" (a vaulted open ended hall) often have high ceilings of more than 3.30m which is also recommended by Givoni (Givoni 1962 and 1976).

Some of the other strategies used in vernacular designs are to reduce the surfaces exposed to the sun and to increase wall thickness in order to provide suitable thermal capacity. The exposed surfaces are also reduced by constructing houses attached to each other with common walls, in a cluster form. Distributing main rooms around a deep courtyard with plants, trees and shrubs in it, has been a very common strategy to decrease solar radiation gain and trap the cool night air for several hours into the next morning (Tavassoli 1980).

In designing buildings for the hot arid zone, openings are of high importance and must get enough attention to minimise direct sunshine into internal spaces. For this purpose, doors and windows are built in small sizes and protected by shading and insulating devices. Windows, wherever possible, are situated high in walls (Saini 1973). Living in basements, especially in summer afternoons, is another strategy to use the relatively low ground temperature, when the air temperature is too hot (Heydari 2000).

Rational planning of vegetation can offer significant shade, which is important for site temperature reductions. Atkinson (1962) has produced a comprehensive list of various available forms of vegetation. These have been set out according to their shape, size and density of foliage, which affect their shade-producing qualities.

Large and deep cisterns under the rooms on the northern side of the courtyard (rooms normally used in the Summer) have been an important device for being filled with cold water in winter and then cooling the surrounding environment through the summer by providing a continuous and natural evaporation of water from their surfaces (Bahadori 1979).

Based on what was discussed above, the climatic housing design strategies, which are considered suitable for the hot dry zone of Iran are summarised in the following pages. The first strategy, using courtyards in the centre of the building, obviously is concerned with the overall design layout of the building. The other three categories, however, discuss strategies that could be used in conjunction with any type or style of design and, as mentioned in the previous chapter, assessing the importance of the overall design of the building against these factors is the main objective of this study.

2.1.1 Central courtyards

One of the specific strategies that is often recommended for housing design in hot climates is housing in a compact layout with some open spaces within. This recommendation is considered important in providing thermal comfort both indoors and outdoors (Heydari 2000). Following paragraphs briefly describe why people, particularly in hot arid climates, have used central courtyard buildings as an answer to their thermal comfort issue in such a harsh weather and why this type of design is one of the most popular solutions to this problem.

According to Givoni (1994), without any cooling system and by appropriate building design, the indoor maximum temperature can be lowered by up to 8°C below the outdoor level. Within a closed indoor space, solar radiation can be eliminated and the mean radiant temperature is usually close to the indoor air temperature. Inside the house people are usually protected from direct exposure to solar radiation, and the radiant heat load is not a significant factor affecting comfort. However, outdoors the reflected solar radiation and emitted long-wave radiation from surrounding hot surfaces like the ground can cause significant radiant heat load and therefore should be minimised.

It must be noted that outdoor spaces can be cooled by systems that may not be used indoors, including wet walls and droplet fountains. Some of the systems suitable for cooling open spaces can use water that is not suitable for indoor evaporative coolers. For example, they can use brackish water, which is often available in arid regions (Givoni 1994).

As Givoni (1994) mentioned, having an outdoor living space (like a courtyard) in the house, cannot guarantee thermal comfort. In fact a poorly designed open space may elevate indoor temperature of adjacent rooms and cause poor ventilation in the rooms located on the leeward side. This has been demonstrated in a study done by Etzion (2003), who measured air temperatures at one-metre height in two courtyards. Both courtyards had concrete pavement over the whole of their ground. Different measurements in both daytime and night showed that the temperatures in the two courtyards were very similar and both were much higher than the ambient air in the open space nearly at the same height. The average minimum temperature was higher by about 0.5°C and maximum by about 2.3°C.

In hot climates the phenomenon of outgoing radiation, whereby the earth and buildings on it lose heat, becomes an important natural cooling system. As Donham (1960) describes in the early morning before sunrise, the outer surfaces of buildings are at their minimum temperature as is the outside air temperature. After sunrise, sunrays make a small angle with the horizon and the effect on the surface is still minimal. As the sun 'moves', the intensity of its radiation becomes greater and the sunlit surfaces are heated up, hence the flow of heat within the surrounding walls and ceilings starts reversing its direction and heat flows inward. At this time the indoor temperature of the rooms is lower than outdoors. The temperature reaches its maximum in the afternoon. After sunset the sky becomes much colder than the external surfaces of the building. Because of this the external surfaces lose heat and the temperature of the adjacent layer of air gradually decreases. The cold air, being denser than the relatively warmer air near the ground, tends to sink down. Exchange between this cold air and the warmer indoor air takes place through the opening in the surrounding walls and the outward heat flow through the materials of walls and roof as well. On the other hand, as evening advances, the warm outdoor air that was heated directly by the sun and indirectly by the warm building rises and is gradually replaced by the already cooled night air from above. This cool air, if entrapped by a courtyard, accumulates around the building in laminar layers and seeps into the surrounding rooms, cooling them (Donham 1960).

These brief descriptions show why people, in order to enhance their thermal comfort, have used the courtyard, and why this phenomenon created the courtyard house concept. This concept, which is briefly explained here and comprehensively examined later, is one of the most popular answers to the issue of placement of open spaces in a house.

Some studies have been directed towards recommending that a small courtyard for providing a satisfactory condition is most suitable (Donham 1960, Olgyay 1963 and Koenigsberger 1973). This is because, if the courtyard's size is kept small enough to achieve shade during the day, it will allow less thermal impact and more heat dissipation from surrounding indoor spaces. Olgyay (1963) has shown that the optimum form of a courtyard is a rectangle in plan having a proportion of 1:1.3. Importantly the height around the courtyard is the most important factor of courtyard plan size. As an experience when traditional houses in Iran were built on one floor the parapets of the houses were built well above the roofline, the reason again being a need to create shade and protection. This also gave the courtyard a greater depth and made the house's courtyard a well-defined, more comfortable place. In many houses another desirable method of creating shade is to construct roof overhangs.

However, most hot arid zones are located in lower latitudes (below 35° North or above 35° South) in which the angle of the sun during the summer is high, close to zenith: this makes the design of self-shading courtyards (which shade themselves by their own geometrical layout) almost impossible. In arid regions shading the outdoor spaces by trees and plants is normally considered one of the best ways for providing comfortable conditions. However, growing trees and other vegetation for the purpose of shading the courtyards is not an easy task, due to the lack of water and the harsh climate. In every traditional courtyard in Iran the use of two or four small gardens (about 1.5 m) and a small pond between them is usual (Memarian, 1998).

Another important element for lowering the air temperature inside a courtyard and, consequently, its adjacent indoor spaces is the paving in the courtyard. In fact treatment can be applied in courtyards to lower the surface temperature by the use of suitable paving materials and cooling the paving of the area itself. Paving heats up quickly causing both painful glare and reflected heat radiation toward the inside of the house (Koenigsberger 1973). In the early morning the paving receives the diffuse radiation coming from the sky and from the surrounding walls. As the sun rises, the ground surface loses heat to the adjacent cold air layer. The rising heated air is replaced by relatively colder air until the air temperature inside the courtyard reaches that of the outside air. The duration of paving exposure to intense radiation is greater than that of any vertical wall; this accounts for the criticality of the treatment of its surface. However, for lowering air temperature the material and colour of paving and the amount of moisture and shade of pavement are important. In the hot dry zone of

Iran burnt clay brick for pavement is one of the most widely used materials. The light colour, the good absorption of water and the ability of evaporation of water in time of need and availability are some of the burnt clay brick's good properties.

It could be observed, as a result of what was discussed in this section, that although this type of house architecture (central courtyard housing) is considered beneficial in some climates, the amount of architectural and constructional details normally associated with this design can significantly confound the effect of the design itself in comparison to other factors. Most of the details discussed so far are unique to this design type. However, there are some other architectural and constructional considerations that could significantly affect the energy performance of any type of design and three of the most important strategies of this kind are explained in the following sections.

2.1.2 Materials

In hot dry areas, external surfaces (such as walls and roof) and their materials are important factors in providing thermal comfort. The major function of the walls in hot dry areas is to protect against solar radiation and high daytime outdoor temperatures, and to control the inward flow of both heat and hot air for most of the day during the summer seasons. In this way heat capacity of the walls is quite important because it moderates the rate of heat flow in and out of the building interior, and hence the indoor temperature fluctuations. On the other hand, such walls cool slowly at night and have higher nocturnal temperatures than low heat capacity structures (Givoni 1976).

Thermal mass can act as a regulator, smoothing temperature swings, delaying peak temperature, decreasing mean radiant temperature and providing better comfort conditions. Givoni conducted an experiment for the effectiveness of mass in lowering the indoor air temperatures. He chose two buildings with the same heat loss coefficient but with different mass levels: a low-mass (conventional stud wall construction) and a high-mass building (insulated concrete walls) were monitored during summer (Givoni 1998). One of the experimental conditions was to close un-shaded windows day and night. The indoor average temperatures of both buildings at different mass levels were different and all were above the outdoor maxima. The maximum temperature elevation of the low mass building was about 6.7°C above the outdoors' maxima while that of the high mass building was about 4.5°C. Fathy (1986) conducted tests on experimental buildings. The materials used in one of the two examined buildings were 50cm thick mud brick walls and roof and prefabricated concrete panel walls and roof with thickness of 10cm in the other building. The air temperature fluctuation inside the mud brick building did not exceed 2°C during the 24 hours period, varying from 21-23°C which is within the comfort zone. On the other hand the maximum air temperature inside the prefabricated building reached 36°C, or 13°C higher than the mud brick model and 9°C higher than outdoor air temperature. The indoor temperature of the prefabricated concrete room is higher than the thermal comfort level most of the day. These examples have shown the importance of mass in buildings and since most of the historical central courtyard houses have used a high-mass construction (normally thick mud brick walls and roofs), it is very important to distinguish between the share of these structures in regulating the indoor temperature as opposed to the share of the central courtyard as a design element.

On the other hand, surface treatment and the selection of a wall's colour will influence the thermal behaviour of the building and can help in reducing the heat load. Light colours will reflect a large part of the incident solar radiation, thus much less heat will actually enter the building fabric. Bansal (1992) performed some experiments on the effect of colour on the interior temperatures in a hot dry climate by using two similar enclosures, one of which was black and the other white. The black enclosure recorded a maximum temperature which was 7°C more than the white painted enclosure during hours of maximum solar radiation. Use of light colours in traditional parts of hot dry cities in Iran shows how people know the importance of colour. External roof colour also is the main determining factor for the roof temperature pattern and consequently for occupants' comfort. The effect of roof colour on its surface temperature is of course related to the thermal resistance and heat capacity of the roof structure. Givoni (1976) argues that the differences between the ceiling temperatures on the black and whitewashed roofs were much greater for a 7cm thick roof than for that of 20cm thick.

2.1.3 Windows

The other building elements that are considered of great importance in the thermal performance of the buildings in hot dry regions are windows. Large windows may increase solar heat gain and glare discomfort, reinforcing the notion that small windows are more suitable in such a climate. But with special design details large windows can provide thermal advantages (Bansal 1992). When highly insulated shutters are added to large operable windows, their thermal effect can be adjusted to varying needs, both diurnally and annually. In summer the shutters can be closed during hot hours. Then light will filter into the house only through the small areas provided by the shutter. In the evening the shutters and the windows can be opened for increasing the rate of cooling of the interior. In winter, large southern windows can provide significant direct solar heating of the interior. Closing the insulated shutters during the night traps the heat indoors and reduces the rate of cooling. This helps to maintain comfortable indoor night temperature (Givoni 1998). It should be important for designers to know that heat gain through windows, per unit area, is much higher than through walls or roofs. The question is: how does the importance of windows in defining the level of energy consumption and thermal comfort compare to that of the positioning of outdoor space in the building design. This is a question that this thesis intends to answer.

2.1.4 Roof

In hot countries it is popularly believed that the roof is the main heating element of a house (Givoni 1976). Thus, a popular idea for providing indoor comfort conditions is to shade the roof more naturally by designing it to suit local traditions. One or two small rooms in the roof level with suitable overhangs have two functions which are shading the roof during the day and providing physiologically comfortable areas during sleep time. These rooms can be used by younger people (considering that during days they are out of the house or with parents for having food and other family activities). In this way the parapets around the roof can be used. Parapets not only make it a safe place for children, but also it is a good element for more shade on the roof. The high parapet has two other benefits: first, it shields the roof from the dusty summer winds and second the courtyards and streets can be narrow, so that the parapets shade the neighbouring elements, reducing the solar heat load.

The shape and height of the roof is also important. In hot areas mud domes are a common means of covering spaces. The form of the dome allows winds to cool its surface easily and it also ensures minimal frequency of intense radiation at any one point. The double dome is considered as an excellent solution to the problem of intense radiation (Heydari 2000). The space between the inner and outer dome acts as an insulation layer. Therefore, under intense summer solar radiation, the outer dome becomes extremely hot, while the inner dome remains cool. Circulation of air between the two domes reduces the radiation problem.

2.1.5 Discussion

So far in this chapter different conventional methods for reducing the energy needs of a building have been discussed. To comply with the requirements of the present research the main emphasis of this discussion was put on one-family residential buildings in hot-arid climates. The strategies mentioned in this literature review could be seen as general guidelines for designing in this climate.

However, it is worth mentioning here another set of strategies that could serve the same purpose. These strategies, which could be labeled as 'adaptive strategies', include precautions practiced by the occupants of the building in order to lower their energy needs. Heydari (2000) lists the following as some of the adaptive strategies practiced in Iranian vernacular houses:

- Selecting the roof and courtyard for sleeping in the hot season.
- Opening windows and doors during sleeping time, while sleeping outdoors.

- Using wooden sofa-beds on the pond in the courtyard for sitting and sleeping
- Using felt carpets during cold season
- Serving hot meals during cold season and cold meals during hot season.
- Changing sleeping time and working time in different seasons.
- Using different clothing for different seasons
- Using the rooms on the shaded side of the courtyard in summer and the opposite side in winter.

If designed and executed properly, these two categories of strategies could have a significant effect on the reduction of the energy needed for heating and cooling of a building through providing an extended number of thermally comfortable hours in all or part of the building spaces, indoors and outdoors. Identifying and understanding these strategies and eliminating their asymmetric effect on different design styles (by either applying them to or removing them from all styles) before starting to compare their effectiveness, will help to clarify the influence of the overall geometric design of the building as the sole comparison metric between all possible design solutions.

2.2 Thermal comfort

Strategies discussed in the previous section were mainly concerned with the energy consumption and, as a result, provided some direct or indirect indications about the thermal comfort inside buildings. This section focuses on methods to quantify and compare the thermal sensation of the occupiers and users of the private open spaces of a house based on the available knowledge of thermal comfort both indoors and outdoors. This thermal sensation is one of the major factors to determine the degree of usability of the exterior grounds of a house, as a potential extra living space for the family (see 1.2.2).

The existing knowledge base on indoor thermal comfort is quite extensive and up-to-date. However, when dealing with outdoor thermal comfort, it is observed that although various researchers have accomplished significant findings in this area, a methodical updated literature review of these works is the missing link in this area of knowledge. The most significant recent collections in this field are the ones provided by Chun et al (2004) concentrating on transitional spaces (like entrances and hallways) and by Ali-Toudert (2005) mainly dealing with street canyons. An obvious lack of a revised literature review, especially after the latest changes in the concept and standards of thermal comfort (as suggested for example by ASHRAE 2004), is observable. This intensifies the need for a revision of the existing knowledge on indoor and, particularly, outdoor thermal comfort both for the purpose of this research and for similar studies. Following pages are presented with the intention to fill this gap in the existing knowledge.

The energy exchanges between a person and the surrounding environment is illustrated in Fig. 5.1 and expressed by the following heat energy balance equation (Fanger 1970):

$$M+W+Q^{*}+Q_{H}+Q_{L}+Q_{SW}+Q_{RE}=S \quad (2.1)$$

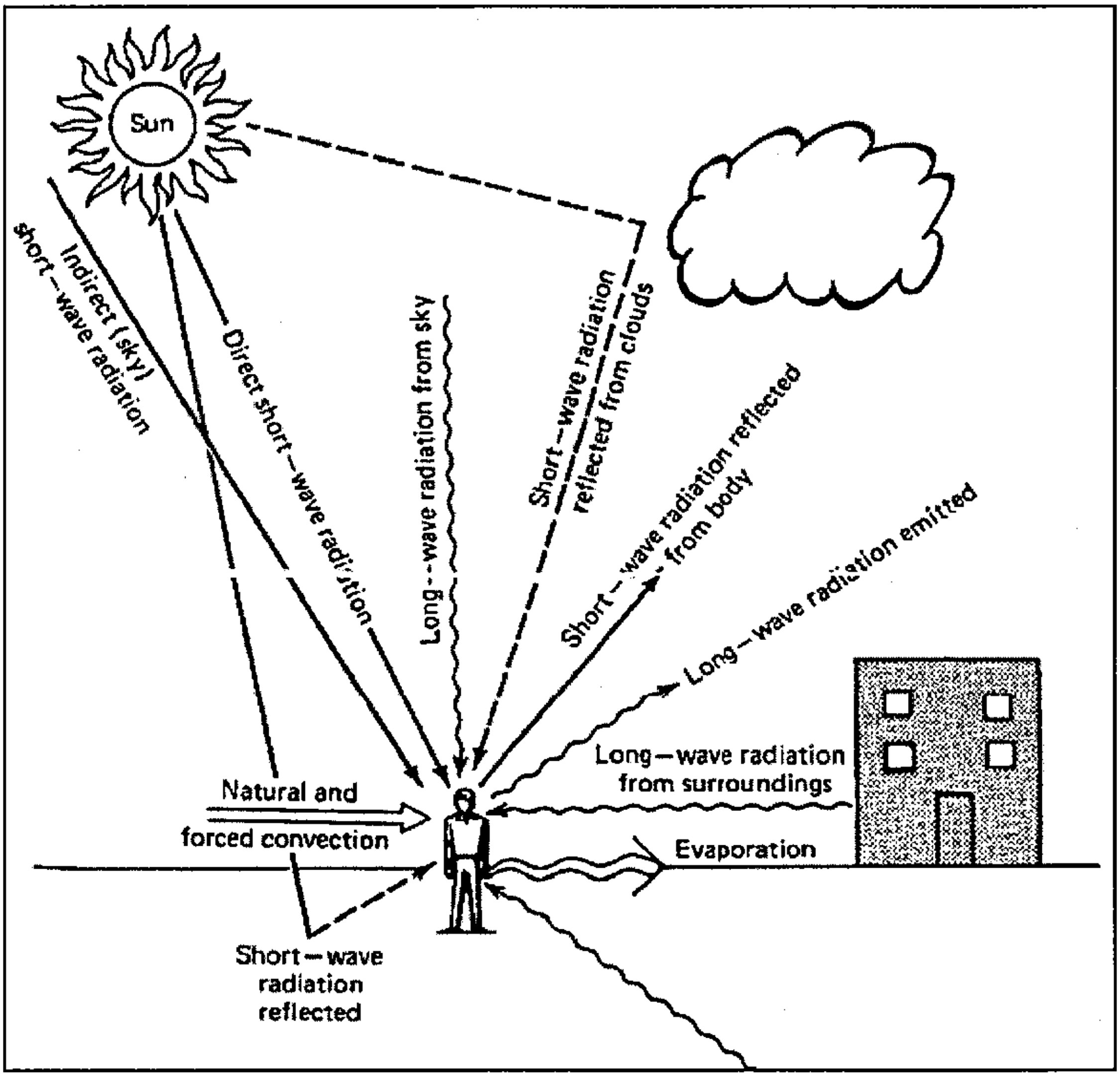


Figure 2.1 The components of the human heat balance (Ali-Toudert 2005 after Houghton 1985)

All terms of equation 5.1 are expressed in (W), where is the metabolic rate (i.e. internal energy production by oxidation of food), W the physical work output, Q^* the net radiation balance of the body, Q_H the convective heat flow (sensible), Q_L the latent heat flow for diffusion of water vapour, Q_{SW} latent heat flow due to evaporation of sweat, Q_{RE} respiratory heat flux (sum of heat flow for heating and humidifying the inspired air) and S is the storage heat flow for heating (positive value) or cooling (negative value) the body.

The detailed mathematical expressions describing each of these terms are thoroughly documented (e.g. Fanger 1970, Gagge et al. 1971, Gagge et al. 1986, Höppe 1984, VDI 1998, ASHRAE 2001a). Basically, the body state influences many of these heat fluxes through body temperatures and skin wetness. The environmental factors also affect a number of individual terms as follows:

$Q_H = f(T_a, v)$; $Q_{RE} = f(T_a, RH)$; $Q_{SW} = f(RH, v)$; and $Q^* = f(T_{mrt})$.

Equation (2.1) is the basis for all human energy balance models for indoors as well as for outdoors. The differences between the various existing models are attributable to their specific methods for calculating personal data required to solve this equation.

2.2.1 Indoor thermal comfort

Although achieving thermal comfort in the living and working space is not a new concern for designers and architects, the first attempts to measure, scale and quantify the sense of comfort by human beings can only be traced back to the 20th century. Before then, the understanding of comfort had only been related to the factors of light, heat and ventilation (Gossauer and Wagner 2007). After the first few attempts to suggest a method for measuring the effect of environment on occupants and users (e.g. Houghton and Yaglou 1923, Mayo 1930, Bedford 1936, Missenard 1948) it was Fanger (1970) who finally came up with a set of equations to explain the nature of thermal interactions between the body and its surrounding environment together with a practical approach for thermal comfort assessment.

This set of equations establishes a theoretical human body in thermal equilibrium with its environment. Metabolic-based heat gains are offset with heat losses through conduction (in a small negligible amount), convection, radiation and evaporation. The thermal comfort equations account for variations in activity level, posture, clothing insulation, air movement, plus dry bulb, wet bulb and radiant temperatures (Anderson 1999). The model he proposed, and later discussed in more details by others such as Doherty (1988) and Oseland (1995), has been the basis for the thermal comfort criteria embedded in standards ASHRAE Standard 55 (ASHRAE 2004) and ISO Standard 7730 (ISO 1994).

Fanger also proposed a method by which the actual thermal sensation could be predicted. His assumption for this was that the sensation experienced by a person was a function of the physiological strain imposed on the person by the environment. This he defined as "the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort values for skin temperature and sweat production at the actual activity level" (Fanger1970). He calculated this extra load for people involved in climate chamber experiments and plotted their comfort vote against it. Thus he was able to predict what comfort vote would arise from a given set of environmental conditions for a given clothing insulation and metabolic rate. Tables of PMV (Predicted Mean Vote) are available for different environments for given clothing and metabolic rates (Humphreys and Nicol 1998). The fact that PMV is an indicator of the mean vote by the users puts a limit on understanding the thermal sensation of individuals. For example, a mean vote of 0 (completely comfortable) for a room could be an average between two votes at opposite ends of the scale range and therefore does not provide any indication on how comfortable the individuals in the room might be.

To correct this restriction Fanger extended the PMV to predict the proportion of any population that will be dissatisfied with the environment. A person's dissatisfaction was defined in terms of their comfort vote. Those who vote outside the central three scaling points on the ASHRAE scale were counted as dissatisfied. PPD (Predicted Percentage Dissatisfied) is defined in terms of the PMV, and adds no information to that already available in PMV (Gossauer and Wagner 2007).

Gagge and Nishi (1977) argued that to consider the human body as one uniform source of heat in interaction with its environment is too assumptive, and so proposed their "two-node model" (Gagge and Nishi 1977) based on considering two different values for body core temperature and skin temperature. Using a more extended knowledge of human physiology as well as the increasing calculation power of modern computers, others elaborated this idea in more detail and added to the number of body layers and parts that needed to be considered separately when interacting with each other and with the surrounding environment. As a result, a number of more sophisticated human thermal regulation models have become available from which the following are mentioned: Stolwijk's 25-node model (Stolwijk and Hardy 1977), Bue's 41-node model (Bue 1989), Fiala's 51-node model (Fiala et al 1999), Wissler's 225-node model (Wissler 1964) and Fu's 3000-node model (Fu 1995).

In general, all these models can be considered as attempts to develop a better understanding and application for Fanger's equations. They are all based on the experiments on average adult subjects in standard clothing and under predetermined environmental conditions in climate chambers.

The basic idea of this category of models, described by Nicol and Humphreys (1998) as "rational" models, could be summarised as follows:

Thermal comfort of a person is defined by three parameters:

a) the body is in heat balance;

b) sweat rate is within comfort limits;

c) mean skin temperature is within comfort limits.

These three conditions cannot be met only by keeping the ambient air temperature within a certain range. In fact, according to Fanger (1970), the interaction of six fundamental factors defines the human thermal environment and its sensation of comfort:

a) Ambient air temperature (T_a).

b) Radiant temperature (T_{mrt}): in which a change of 1°C can be offset by a 1°C change in T_a.

c) Wind speed: with a change rate of 0.1 m/sec for each 0.5°C change in T_a (up to 1.5°C).

d) Humidity: a 10% change in relative humidity can be offset by a 0.3°C change in T_a.

e) Metabolic rate: in which an increase of 17.5 Watts (above resting level) is equivalent to a 1°C increase in T_a.

f) Clothing insulation (clo): a change of 1 clo is equivalent to a T_a change of 5°C at rest and 10°C while exercising. (Shapiro and Epstein 1984)

This class of thermal comfort models can produce repeatable predictions on the level of thermal comfort under standard and constant conditions in climate chambers, but in dealing with the constantly changing conditions of real living and working spaces they show serious restrictions. De Dear and others (1997) demonstrated that in their field surveys the level of dissatisfaction expressed by users was lower than that predicted by the PPD model. It seems like, in real life, "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol and Humphreys 2006). In other words, people show some level of adaptation with their environment and in more extreme conditions this adaptation becomes more evident. This idea provided the foundation for a new kind of thermal comfort model called by De Dear and others (1997) the "adaptive model".

This adaptive approach accounts for the dynamic relation between people and their everyday environments, paying attention to the adaptations people make to their clothing and to their thermal environment to secure comfort (De Dear et al 1997). The principal research method is field survey. People are asked for their response to their thermal environment, which is measured at the time. Notes of the clothing and of the activity may be taken, from which the thermal insulation of the ensembles and the metabolic rates of the people can be estimated. The opening or closing of the windows, the raising or lowering of blinds, and the switching on or off of fans may be noted, together with any other actions that people take to ensure their thermal comfort (Humphreys et al 2007).

The adaptive model, as a result of the field surveys, proposes that in addition to the 6 factors listed by Fanger (temperature, humidity, thermal radiation, wind speed, clothing insulation and activity) factors like exposure time, human physiological condition, psychological perception, and adaptive behaviours also affect thermal comfort of individuals (Nikolopoulou & Steemers 2003, Soligo et al. 1998,; Stathopoulos et al. 1999).

One of the important conclusions made by the adaptive model is that people show more resistance to cold weather in winter time compared to summer and also show more resistance to heat in summer in comparison to winter. In other words, the comfort temperature (T_c) is a function of outdoor temperature (T_o) :

$T_c = 13.5 + 0.54\ T_o$ (2.2) (Humphreys and Nicol 2000)

This was reflected in ANSI/ASHRAE Standard 55-2004, "Thermal Environmental Conditions for Human Occupancy" as two separate comfort zones for summer and winter.

2.2.2 Outdoor thermal comfort

The early comfort assessment methods applied outdoors have generally been adjusted from those originally conceived for indoors, and are based on the assumption that the conventional theory of thermal comfort developed for indoor applications can be generalized to outdoor settings without modification. However, this approach has been proved inappropriate (Becker et al. 2003, Nikolopoulou et al. 2001, Spagnolo & De Dear 2003). When outdoors, people expect different climatic conditions and usually dress differently, according to the prevailing weather conditions. In addition, people outdoors may be exposed to intense solar radiation and winds, which will modify greatly their response towards the environment (Givoni & Noguchi 2004). Owing to the range of experiences and expectations of people outdoors, it is hypothesized that the acceptable comfort range of outdoor spaces should be wider than that of the indoor context (Jitkhajornwanich & Pitts 1998, Spagnolo & de Dear 2003). Outdoor thermal comfort has been receiving increasing attention and a diversity of studies including field surveys, wind tunnel experiments and computer simulations have been conducted in the past couple of decades (Arens & Bosselmann 1989, Ramirez 1991, Ramos & Steemers 2003). The following material outlines the most relevant studies to the area of concern of the present research (assessment of thermal comfort in small enclosed outdoor spaces like courtyards etc.) and discusses their results and conclusions.

Leonard Hill's research (1919) is cited as the first recorded attempt to correlate atmospheric cooling power with sensation. He established the Kata thermometer for measuring the cooling rate of the atmosphere. His dry Kata was similar to an ordinary thermometer heated to a temperature above that of normal human blood (37 $°C$ or 98.4 $°F$). With the thermometer exposed to the path of wind, but shaded from the direct rays of the sun, the time required for the alcohol or mercury in the bulb to cool from one Fahrenheit degree above to one degree below blood temperature was recorded and averaged for a temperature drop of one degree.

He expressed his observations on the cooling rate of the wind via the following formula:

$$H = (0.15 + 0.182\sqrt{v})(98° - T) \tag{2.3}$$

Where H is the dry cooling power of the atmosphere ($mCal/cm^2 \cdot S$), v the wind velocity (*mph*) and T the dry-bulb temperature ($°F$).

He also measured the wet cooling power of the atmosphere by a Kata thermometer wrapped in a piece of wet cloth. The added rate of cooling by evaporation was recorded by reading the thermometer in the same manner as the dry Kata. The results of these experiments were expressed in the form of a second equation:

$$H' = H + (0.085 + 0.102\sqrt[3]{v}) \times \sqrt[3]{(F - f)^4} \tag{2.4}$$

Where H', *H* are the wet and dry cooling power of the atmosphere ($mCal/cm^2 \cdot S$) respectively, v the wind velocity (*mph*), *F* the saturation vapour pressure at 36.5 $°C$ (45.4 mm Hg), and *f* is the vapour pressure of the air (mm Hg).

During the 1920s and 1930s numerous students and investigators of the subject, including Hill, Angus, Newbold, Vernon, Bedford, Warner, McConnell, Yaglou, Dokoff, Griffith, Flack, Soper, Gold, Hargood, Ash and others perfected or used the Kata thermometer and led to its general, although limited, acceptance (Siple and Passel 1945). Some of these studies concentrated on improving Hill's Kata thermometer or replacing it by a device that could represent the content, shape and size of the human body or could account for the effect of irradiative heat gains in a better way. To name only some of these devices, the Davos frigorimeter (Dorno 1926), the heated copper globe (Vernon and Warner 1932), the recording Eupatheoscope (Dutton 1933) and the Pfleiderer-Buttner frigorigraph (1937) could be mentioned.

Among this category of studies, Ernest Gold's research (1935) is of special importance, particularly for the present study. Gold came up with a means of predicting the thermal sensation of a human body when exposed to the outdoor environmental factors. Based on the data gathered from his own observations, he introduced a simple formula, describing the heat loss of a body as a simple function of air temperature and wind speed:

$$H = (36.5 - T_a) \times (11.3 + 20\sqrt{v}) \quad \text{(2.5)(Gold 1935)}$$

Where H is the heat loss of the body ($cal/m^2/hr$), T_a the air temperature ($°F$) and v the wind speed (*mph*).

He also proposed a modifying factor to account for different levels of sunshine intensity:

a reduction of 630 W/m^2 in the heat loss when in full sun;

290 W/m^2 in light cloud;

and 125 W/m^2 with thick clouds.

Based on his observations, he suggested a descriptive thermal sensation scale of eleven grades ranging from “bitterly cold” to “pleasant” to “unbearably hot”. This descriptive approach, with modifications, became the basis for explaining the level of thermal comfort in all subsequent models.

Parallel to these studies, there is evidence of extensive research on the nature of human thermal comfort in Germany during the 12 years leading to the Second World War. These studies are, to date, largely unknown but one can suggest that their results have been considered in the papers published in the U. S. in the early post-war years. For example, the U. S. army researchers, Major Paul Siple and Charles Passel, in the paper “Measurements of Dry Atmospheric Cooling in Subfreezing Temperatures” published in 1945 (Siple and Passel 1945), list the works of 11 different German researchers from that period in their list of references without mentioning their works in the main text.

Siple and Passel introduced the wind-chill index, one of the first thermal comfort indices applicable to the outdoor environment that, with proper modifications, can still be used for specific weather conditions. The results of their studies give a new equation for the effect of outdoor air temperature and wind speed on the heat loss of the human body:

$$H = (33 - T_a)(\sqrt{100v} + 10.45 - v) \qquad (2.6)$$

Where H is the heat loss from the body ($Kcal / m^2 hr$), v the wind speed (m/s) and T_a the air temperature ($°C$).

The studies carried out by Hill, Gold and Siple-Passel all deal with environments with low, sometimes very low, temperatures. Other studies (e.g. MacFarlane 1958, Webb 1959) showed a discrepancy of comfort perception between people of different climatic zones. MacFarlane even suggested a method of adjusting comfort temperature zones for variations in latitude, relative humidity, solar radiation, and wind speed (Penwarden 1973).

In an attempt to combine MacFarlane's idea of "thermal comfort zones" with Humphrey's model for thermal comfort in indoor environments, Penwarden (1973) suggested the following formula for predicting outdoor thermal comfort with an emphasis on direct solar radiation:

$$T_a - T_b = M_{Du}R_b + kM_{Du}R_c + \frac{kM_{du} + S}{4.2 + 13\sqrt{v}} \qquad (2.7)$$

T_b: Body core temperature = (*37 °C*)

T_a: Outdoor air temperature (*°C*)

M_{Du}: Metabolic rate of heat production per square metre of body surface (*W/m²*)

k: Proportion of metabolic heat dissipated by means other than evaporation ≈ 0.8

R_b: Thermal resistance of body tissues (m^2. *°C/W*) ranging from 0.04 m^2.°C/W (onset of sweating) to 0.09 m^2.°C/W (onset of shivering)

R_c: Thermal resistance of clothing (m^2.*°C/W*) (1 clo = 0.155 m^2.°C/W)

S: Solar heat input per square metre of body surface (W/m^2) Max. about 120 W/m^2

v: Wind speed (*m/s*)

A large number of studies have been conducted in recent decades to determine specific outdoor comfort criteria for specific climates (for example Jithkajornwanich and Pitt's survey in Thailand 1998, Forwood and associates' survey in Australia 2000, Sasaki and others' study on four different cities in Japan 2000, Ahmed's Research in Bangladesh 2003, Givoni and colleagues' research in Japan and Israel 2003 and Nicol and others' study in the UK 2006). Among these local studies, a few deal with smaller outdoor spaces and, therefore, are of particular importance for the current research.

One of the first major studies in this field was Tacken's experiment (1989) to investigate the comfortable range of wind speed for outdoor relaxation in urban areas of Netherlands. To show how wind speed can, in relation to solar radiation, affect the sense of comfort outdoors, he developed the following formula:

$$P = -0.329 + 0.215T_a - 0.6v + 0.0024S \tag{2.8}$$

where *P* is the perception of climate, scaled from 1 to 7, with 4 representing neutral conditions, T_a air temperature (°C), v wind speed (*m/s*) and *S* solar radiation on land (W/m^2).

The EU funded project, RUROS (Rediscovering the Urban Realm and Open Spaces), in 2001 had aimed to "examine and evaluate a wide range of comfort conditions -thermal, visual, audible - across Europe, and develop a series of comfort models for different climatic contexts at the scale of the urban block". As part of this project, thermal comfort surveys and modelling have been carried out in 17 case study sites all over Europe (Ramos & Steemers, 2003).

The case study in Greece that was conducted by Nicolopoulou resulted in particularly interesting conclusions. This study observed a large pool of 1500 subjects during four different seasons in Athens (Nikolopoulou et al., 2003). As a result, a formula for outdoor thermal comfort as a function of air temperature, globe temperature, wind speed and relative humidity was developed:

$$ASV = 0.061T_a + 0.091T_{g-a} - 0.324v + 0.003RH - 1.455 \quad (2.9)$$

Where:

ASV: Actual sensation vote, scale from -2 (very cold) to +2 (very hot) and neutral at 0.

T_a: Air temperature (°C)

T_{g-a}: Difference between globe temperature and air temperature (T_g-T_a) (°C)

v: Wind speed m/s

RH: Relative humidity %

This study also suggests a replacement formula to predict the ASV based on the data from a nearby meteorological station:

$$ASV = 0.034T_{a'} + 0.0001S' - 0.086v' - 0.001RH' - 0.412 \quad (2.10)$$

Where:

ASV: Actual sensation vote, scale from -2 (very cold) to +2 (very hot) with 0 representing the neutral sensation

T_a: Air temperature at the meteorological station *(°C)*

S': Solar radiation at the meteorological station *(W/m²)*

v': Wind speed at the meteorological station *(m/s)*

RH': Relative humidity at the meteorological station *(%)*

The study points out that the main problem with deriving a mean radiant temperature from solar radiation at the meteorological station is ignoring the effect of shading and therefore achieving the same ASV for both shaded and sunny areas in one space.

A critical issue in assessing the human thermal comfort outdoors is the need for the mean radiant temperature (T_{mrt}), which sums up all short-wave and long-wave radiation fluxes absorbed by a human body. T_{mrt} is the key variable in evaluating the thermal sensation outdoors under sunny conditions regardless of the comfort index used (e.g. Mayer and Höppe 1987, Jendritzky et al. 1990, Mayer 1993, Spagnolo and De Dear 2003). T_{mrt} is, by definition, the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure (ASHRAE 2001b). However, its accurate calculation in outdoor spaces is not easy, particularly in complex urban environments. This, certainly, explains the usual focus on air temperature and air humidity in comfort related studies as these are easier to measure.

Theoretically, T_{mrt} applicable outdoors is given by the following formula (Fanger 1970):

$$T_{mrt} = \left[1/\sigma_B \left(\sum_{i=1}^{n} E_i F_i + \frac{\alpha_k}{\varepsilon_p} \sum_{i=1}^{n} D_i F_i + \frac{\alpha_k}{\varepsilon_p} f_p I \right) \right]^{0.25} \tag{2.11}$$

where the surroundings are divided into n isothermal surfaces, for each one E_i (Wm^{-2}) is the long-wave radiation component ($Ei = \sigma_B \ \varepsilon_i \ T_i^4$), D_i (Wm^{-2}) is the diffuse and diffusely reflected short-wave radiation component, F_i is the angle weighting factor, I (Wm^{-2}) is the direct solar radiation impinging normal to the surface, f_p is the surface projection factor which is a function of the sun height and the body posture, α_k is the absorption coefficient of the irradiated body surface for short-wave radiation (≈ 0.7), ε_p is the emissivity of the human body (≈ 0.97), and σ_B is the Stefan-Boltzmann constant $(\sigma_B = 5.67 \cdot 10^{-8}\ Wm^{-2}K^{-4})$.

The calculation of the angle factor F_i is the most problematic aspect when dividing the environment into several surfaces. A procedure for calculating the angle factors is given by Fanger (1970) for simple shapes, but the task becomes much more complicated for complex urban forms and simplifications are thus necessary.

Several calculation procedures for T_{mrt} do exist, depending on whether it is modelled or measured. As discussed before, the procedure used in this thesis is based on modeling. However, a full understanding of the modeling process needs a careful consideration of methods of direct measurement of mean radiant temperature. One method, for instance, is to divide the human surroundings in two hemispheres upwards and downwards and with the weighting factor F_i set to 0.5 for each of the two directions (e.g. Jendritzky et al. 1990, Pickup and de Dear 1999). Although easier to use, this method is probably only reliable for unobstructed open spaces. Obstruction effects may be added if fish-eye photography is used to replace F_i (Watson and Johnsson 1988, Chalfoun 2001). Yet, all surface temperatures as well as direct and diffuse short-wave radiation components are still required.

To avoid such difficulties, the most suitable method would be to use an integral radiation instrument. Such an instrument exists for indoor purposes, i.e. a globe thermometer (e.g. Givoni 1976, ASHRAE 2001b). The globe thermometer consists of a hollow sphere (usually 15 cm in diameter), with a flat black paint coating and a thermometer bulb at its centre. The temperature assumed by the globe at equilibrium results from a balance between the heat gained or lost by radiation and convection. Empirical formulas derive T_{mrt} from the globe temperature T_g, together with T_a and v (Givoni 1976, ASHRAE 2001b). Alternatively, a comfort index can be directly calculated, namely the Wet Bulb Globe Temperature (WBGT), usually used for assessing comfort in working spaces (Givoni 1976, ISO 1989, ASHRAE 2001b).

The globe thermometer gives a good approximation of T_{mrt} indoors, where the heat irradiated from the surroundings is rather uniform. However, the globe thermometer is less suitable outdoors for several reasons, including the non-homogeneity of the radiant environment induced by the additional solar beam radiation. Moreover, because of its spherical shape, the globe thermometer may be well approximated for a seated person, as it averages the absorbed radiation equally from all directions, but not for a standing person for which the lateral fluxes are dominant. T_{mrt}, integrally obtained, assumes equal energy absorption from a human body in both long-wave and short-wave ranges, and the black colour overestimates the absorption of short-wave radiation, unless it is replaced by a grey globe more suitable to describe normal clothing (ASHRAE 2001b). Finally, the globe thermometer is not convenient because it needs a relatively long time to reach equilibrium (15-20 minutes). Alternatively, one can use a smaller and light-coloured sphere for faster response of the instrument (ASHRAE 2001b). Despite these disadvantages, it has been implemented for outdoors issues, e.g. for workspaces outdoors (wet globe bulb temperature, WGBT) or even in social surveys (Nikolopoulou et al. 2001, RUROS 2004). To date, there is no reliable instrument for integral measurement of T_{mrt} outdoors, even though some attempts have been made (e.g. Brown and Gillespie 1986, Krys and Brown 1990).

With respect to the issue of outdoor thermal comfort in a rectangular courtyard, the modelling technique adopted in this study for measuring T_{mrt} (°C) is based on the technique proposed by Höppe (1992) for considering all radiation fluxes, angle factors, human shape, etc. in the calculations. In this method, the surrounding environment is divided into six main directions (upwards, downwards and the four lateral orientations) and T_{mrt} expressed by:

$$T_{mrt} = \left[S_{rad} / \left(\varepsilon_p \cdot \sigma_B\right)\right]^{0.25} - 273.2 \tag{2.12}$$

with S_{rad} given by:

$$S_{rad} = \sum_{i=1}^{6} W_i \left(\alpha_k \cdot K_i + \alpha_i \cdot L_i\right) \tag{2.13}$$

Here, the related angle factors are the percentage of the hemisphere taken up by each part of the body in each direction and expressed as a fraction (W_i), the short-wave (K_i in Wm^{-2}) and long-wave (L_i in Wm^{-2}) heat fluxes are summed as the mean radiation flux density (S_{rad} in Wm^{-2}). W_i equals 0.22 for lateral directions and 0.06 for upwards and downwards directions for a standing body that is assumed to be cylindrical. Pyranometers and pyrgeometers, arranged in the six directions, are required for the measurement of the short-wave and long-wave radiation fluxes, respectively. This method is accurate but costly and time-consuming, making it difficult to implement in extensive measuring campaigns. Hence, the lack of an easy and reliable method for determining T_{mrt} accounts for the main difficulty in conducting comprehensive investigations on comfort outdoors. To tackle this problem, the analytical approach developed in this research for modelling surface temperatures in a courtyard for specific situations (Chapter 3) uses the radiosity approach to integrate all long-wave and short-wave radiative heat exchanges to and from a surface into one metric and also applies a number of other simplifications to reduce the number of surfaces involved in the microclimate of a courtyard in order to assess their interactions more easily.

Modelling T_{mrt} also requires simplifications. Surface temperatures are here an additional limitation, and are only accurately determined if substrate and wall heat storage are included. The method used in the outdoor environment simulation programme ENVI-met relies on sky view factors, and is detailed in the next chapter.

2.2.3 Outdoor thermal comfort indices

A large number of thermal indices exist and this might be confusing at first, but in fact, most of them share many common features and can be classified into two groups: *empirical* or *rational*. These indices are well documented (e.g. Givoni 1976, Houghton 1985, ASHRAE 2001a) and some of them are listed as examples:

Index	Definition
Empirical indices	
ET Effective Temperature	set in Monograms and represent the instantaneous thermal sensation estimated experimentally as a combination of T_a, RH and v
RT Resultant Temperature	comparable to ET but tested for a longer time to meet assumed thermal equilibrium
HOP Humid Operative Temperature	temperature of a uniform environment at a relative humidity RH = 100% in which a person loses the same total amount of heat from skin as the actual environment (comparable to ET* but RH equals 50% for HOP)
OP Operative Temperature	arithmetic average of T_a and T_{mrt}, that is including solar and infrared radiant fluxes weighted by exchange coefficients
WCI Wind Chill Index	based on the rate of heat loss from exposed skin caused by wind and cold and is function of T_a and v, suitable for winter conditions

Rational indices	
ITS Index of Thermal Stress	assumes that within the range of conditions where it is possible to maintain thermal equilibrium, sweat is secreted at sufficient rate to achieve evaporative cooling.
HSI Heat Stress Index	ratio of the total evaporative heat loss E_{sk} required to thermal equilibrium to the maximum of evaporative heat loss E_{max} possible for the environment, for steady-state conditions (S_{skin}=S_{core}=0) and T_{sk} = 35°C constant
ET* new Effective Temperature	temperature of a standard environment (RH = 50%, $T_a = T_{mrt}$, v < 0.15 ms_{-1}) in which the subject would experience the same sweating SW and T_{sk} as in the actual environment. It is calculated for light activity and light clothing.
SET* Standard Effective Temperature	similar to ET* but with clothing variable. Clothing is standardized for activity concerned. Reference indoor conditions are: $T_{mrt} = T_a$; RH = 50% ; v = 0.15 ms_{-1}.
OUT_SET* Outdoor Standard Effective Temperature	similar to SET* but adapted to outdoors by taking into account the solar radiation fluxes.
PMV and PT Predicted mean vote Perceived Temperature	PMV expresses the variance on a scale from -3 to+3 from a balanced human heat budget and PT the temperature of a standardized environment which achieves the same PMV as the real environment. Clothing and activity are variables.
PET Physiologically Equivalent Temperature	temperature at which in a typical indoor setting: $T_{mrt} = T_a$; VP = 1200 Pa ; v = 0.1 ms_{-1}, the heat balance of the human body (light activity, 0.9clo) is maintained with core and skin temperature equal to those under actual conditions. unit: °C.

Table 2.1 Selected thermal comfort indices for indoors and outdoors (after Ali-Toudert, 2005)

2.2.4 Index selection process

The indices of the former group (empirical indices), generally developed earlier, are based on measurements with subjects or on simplified relationships that do not necessarily follow theory (ASHRAE 2001a). These are often limited to the estimation of the combined effect of air temperature, air humidity and air speed on people in sedentary activity (Givoni 1976). Yet, these empirical indices ignore the important role of human physiology, activity, clothing, and other personal data (height, weight, age, sex). Rational indices are more recent, promoted by the recent development of computing techniques, and rely on the human energy balance. Here, the heat transfer theory applies as a rational starting point to describe the various sensible and latent radiation flux exchanges, together with some empirical expressions describing the effects of known physiological regulatory controls (ASHRAE 2001a). It is , therefore, more relevant to use one of the indices in the second category for the purpose of this research and since the main concern here is the thermal sensitivity of the users of the outdoor spaces, the choice between the thermal comfort indices is narrowed down to the last three indices in the list: OUT_SET*, PMV and PET.

Comparing these three indices, a number of remarks could be made about them and their limitations:

- Theoretically, PET and OUT_SET have the advantage on PMV in that it takes into account the thermoregulations of a human body and are therefore more accurate for extreme conditions (typically outdoors).

- To choose between PET and OUT_SET*, the two programs were tested for identical hot outdoor conditions (using the data from Chapter 3) and the same I_{cl} and metabolic rate. OUT_SET* provided systematically lower values, following a linear relationship: OUT_SET* = 0.73 PET + 3.1, with a very high correlation coefficient R = 0.9998. In fact, OUT_SET* is about 27 % lower because OUT_SET* considers a relative humidity RH = 50 % in the reference indoor situation which is changing with Ta. This interdependence inhibits partly the assessment of thermal stress, whereas PET considers a vapour pressure of 12 hPa which is a constant water content in the air independent from Ta. Hence, this makes PET more accurate than OUT_SET.

Based on this selection process, the thermal comfort index PET (Physiologically Equivalent Temperature) is chosen as the metric for the prediction of thermal sensation of the users of the outdoor spaces in this specific study. However, it has to be mentioned here that for studies dealing with subjective votes obtained from social surveys, which must take into account the actual personal data, PMV and OUT_SET* seem to be better choices. That is because they set I_{cl} and the activity as variables, which means that the human adaptive behaviour is included, whereas these are kept invariable in PET, meaning that only the thermal environment is assessed. However, since the main emphasis of the present study is on analytical assessment of thermal comfort (as opposed to subjective approach), PET demonstrates a higher suitability to the needs of this research.

3. ■ Simulating outdoor environments

Open spaces of small-scale buildings, which are the main concern of the present research, have been reported to provide a microclimate effect showing different climatic conditions from their surroundings (Givoni 1994; Etzion 2003). This means that, when dealing with, for example, a building with a courtyard, the air temperature measured inside the courtyard normally can be different from the air temperature above the roof top. This was also supported by the findings of the measurements conducted at Loughborough University (Malekzadeh and Loveday 2008; please see Appendix A).

Therefore, the first step towards finding the impact of the surrounding environment on the thermal environment of a building is to determine this surrounding environment in an acceptable level of detail. This section deals with available methods for solving this problem. One of the introduced tools will be chosen, validated and used for further analysis of thermal interactions of the building and its surroundings.

3.1. Outdoor simulation programmes

The use of numerical methods for urban climate issues has a distinct advantage over comprehensive field measurements. Their "versatility in dealing with the manifold variables and atmospheric processes" make them increasingly popular (Arnfield 2003). Urban climate models can be first classified according to their scale, which can range from kilometres to a few centimetres. Usually, models developed for urban climate purposes, like studying urban heat islands, use a large space resolution (e.g. Gross 1991, Masson 2000). These are probably more suitable for urban planning issues (scale up to 1/5000) rather than for urban design issues (~ 1/500). The following review addresses the microclimatic numerical models from the latter category, in which scales are more relevant to the house and yard dimensions of interest of this research.

Urban microclimate models vary substantially according to their physical basis and their temporal and spatial resolution. At the microscale, three-dimensional (3D) wind flow models are the most well founded (e.g. Eichorn 1989, Johnsson and Hunter 1995), while those including all hydrological, thermal and energy processes are very few, inter-alia because very time-consuming to calculate the multiple effects of all of these climatic variables on each other. Such models are often simplified by assuming several parameterisations and limitations in order to save time and solve problems linked to variables that are difficult to determine. Typically, these models use simplified turbulence schemes (e.g. Mills 1993, Arnfield 2000). Urban canyon models are also typical examples: 2D rather than 3D, they focus on the prediction of energy fluxes and assume predefined street configurations, with buildings of uniform shape and height, dry surfaces, no vegetation (no latent heat) and no heat storage in the building fabric (e.g. Herbert et al. 1998). Alternatively, models which combine 3D flow modelling and 2D energy modelling are faster and more accurate (e.g. Arnfield et al. 1998). Other models are more empirical and are based on equations derived from few available measured data, which may make them context specific, e.g. Nunez and Oke (1980) or the CTTC model (Swaid and Hoffman 1990, Shashua-Bar and Hoffman 2000). Moreover, many of these models deal with the open space volume as a whole, i.e. all calculations are made for one point at ground level, and spatial differences within the open space are not considered. By contrast, CAD-based models seek to reproduce with precision the 3D outdoor scene, as these models are especially relevant to designers (e.g. Teller and Azar 2001, Asawa et al. 2004) and possibly assess the interdependence between indoors and outdoors in terms of daylight and sunlight availability on the outdoor surfaces, e.g. SOLENE (Groleau and Miguet 1998). The focus in these models is on the calculation of the surface temperatures and mean radiant temperatures that form the boundary surfaces of the open space. Yet, most of the weather data (wind speed, T_a, etc.) are assumed to be known.

Furthermore, very few microclimate models assess the thermal comfort that result from the urban microclimate changes (Teller and Azar 2001, Asawa et al. 2004). This is mainly due to the difficulties in determining the radiation fluxes between the surroundings of a human body and complex urban areas. The issue of modelling outdoor thermal comfort is thus often dealt with using simplified and averaged methods, in which many atmospheric processes are removed. These are then replaced by data set as inputs by the user, which assumes their availability (e.g. daily data for v, T_a, RH). For instance, thermal comfort in the model TOWNSCOPE (Teller and Azar 2001) is calculated on a daily basis, however, with T_a, v, RH, and T_s assumed as mean daily average values that are held constant during the simulation. Clearly, this is a very coarse approach.

Finally, a decisive aspect in choosing a model is the output information. The outputs may vary from only one variable prognosis, e.g. Ta (Swaid and Hoffman 1990), to a detailed microclimate description, e.g. ENVI-met (Bruse 1999).

3.2. ENVI-met

Although the more recent version, 3.1, of the three dimensional model ENVI-met was introduced during the completion of this research, the version used here, due to its availability at the time of initiation of the study, is version 3.0 (Bruse 1999). Ali-Toudert (2005) mentions that the major advantage of ENVI-met is that it is one of the first models that seeks to reproduce the major processes in the atmosphere that affect the microclimate on a well-founded physical basis (i.e. the fundamental laws of fluid dynamics and thermodynamics). According to the objectives of the present work, ENVI-met presents several advantages:

1. ENVI-met simulates the microclimatic dynamics within a daily cycle. The model is in-stationary (i.e. the total heat loss from the model does not have to be equal to the total heat production) and non-hydrostatic (does not assume equal air pressures for all points at the same height) and predicts all exchange processes including wind flow, turbulence, radiation fluxes, temperature and humidity.

2. A detailed representation of complex outdoor structures is possible, i.e. buildings with various shapes and heights or design details like galleries and irregular geometrical forms. This makes it suitable for modelling and predicting conditions in a courtyard. The vegetation is handled not only as a porous obstacle to wind and solar radiation, but also by including the physiological processes of evapotranspiration (evaporation and plant transpiration from the earth's land surface to atmosphere) and photosynthesis. Various types of vegetation with specific properties can be used. The soil is also considered as a volume composed of several layers and the ground can be of various types.

3. The high spatial resolution (up to 0.5 m horizontally) and the high temporal resolution (up to 10 s) allow a fine grading of the microclimatic changes, especially sensible to geometry and pertinent for thermal comfort issues since these dimensions are of human scale.

4. A key variable for outdoor comfort, i.e. mean radiant temperature T_{mrt} of surrounding surfaces, is also calculated.

Fig. 3.1 shows the construction scheme of ENVI-met, which is composed of a 3D core model (including atmospheric, vegetation and soil sub-models) and 1D border model. The task of the 3D core model is to simulate all processes inside the actual model area. The upper horizontal boundary and the vertical windward boundary act as interface of the 1D border model and the 3D core model. The 1D border model extends the simulated area to the height H = 2500 m (i.e. an average depth of the atmospheric boundary layer) and transfers all start values to the upper limits of the 3D volume needed for the actual simulation.

The core area to be simulated is a volume of the dimensions (X, Y, Z) plotted into n grid modules. Z is determined by the maximum height H_{max} of the urban elements within the model ($Z \geq 2H_{max}$). Each module (Δx, Δy, Δz) can either be a part of a building, of vegetation, or of an open space (e.g. courtyard) and possible oblique urban forms have to be approximated in steps. At ground level, the first grid is vertically subdivided into five equal parts in order to record thoroughly the microclimate near the surface.

The soil model provides the system with the surface temperatures and humidity. The soil model is 1D, except for the grids of the ground surface which are connected in 3D for ensuring homogeneity. The nesting grids consist of a "buffer zone", which acts as an offset of the actual edges of the model area in order to avoid numerical disturbances, i.e. boundary effects. The nesting grids also ensure a representative 3D profile of the wind at the windward boundary by adjusting the initial 1D wind profile. These grids get progressively larger as their distance from the core model increases and are composed of two soils types. The nesting area extends at least to double the height of the highest obstacles in the model area (2Hmax) beyond the actual modelled area.

The equations that govern ENVI-met are too numerous to be presented in detail here. Only parts of the model documentations (Bruse and Fleer 1998, Bruse 1999, Bruse 2004, Ali-Toudert 2005) that are directly related to the present study are quoted in this section.

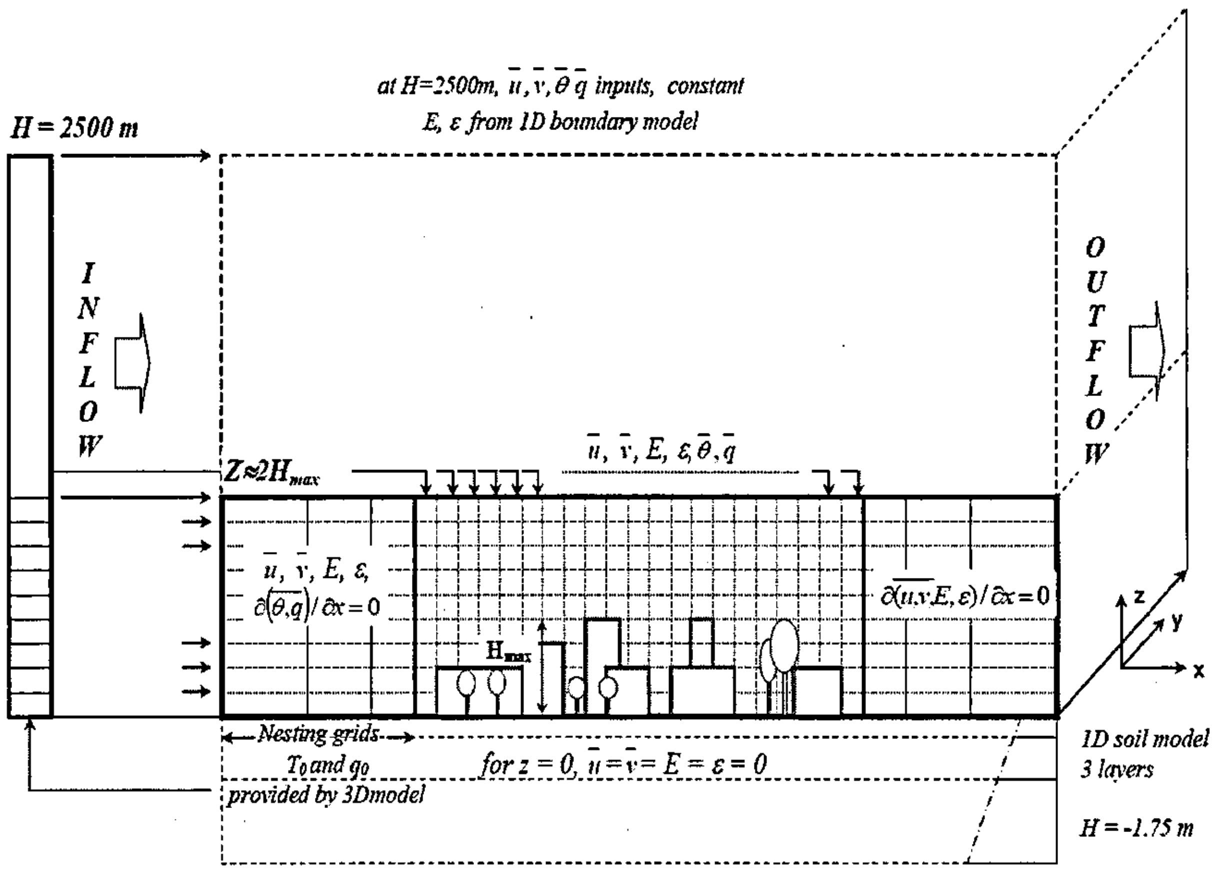


Figure 3.1 General schema of the ENVI-met model including the boundaries (Ali-Toudert 2005)

3.2.1. The atmospheric model

The atmospheric model predicts the evolution of the wind flow (speed and direction), turbulence, temperature, humidity, short-wave and long-wave radiations fluxes. It is based on the fundamental laws of dynamics and thermodynamics of fluids, i.e.

equations of conservation of mass, momentum, heat and moisture (e.g. Garrat 1992).

The distribution of the potential temperature θ and the specific humidity q inside the atmosphere is given by the combined advection-diffusion equation with internal source/sink terms:

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = K_h \left(\frac{\partial^2 \theta}{\partial x_i^2} \right) + \frac{1}{c_p \rho} \frac{\partial R_{n,lw}}{\partial z} + Q_h \tag{3.1}$$

$$\frac{\partial q}{\partial t} + u_i \frac{\partial q}{\partial x_i} = K_q \left(\frac{\partial^2 q}{\partial x_i^2} \right) + Q_q \tag{3.2}$$

where Q_h and Q_q are used to link heat and vapour exchanges between the foliage surface and the surrounding air. These quantities are provided by the vegetation model and since this study intends to minimise all effective factors other than the geometry of the building, the chosen vegetation model will effect in a value of zero for both Q_h and Q_q. K_h and K_q are the diffusion coefficients for heat and vapour. The vertical divergence of long-wave radiation $\partial R_{n,lw}/\partial z$ accounts for cooling and heating effects of radiative fluxes.

The atmospheric long-wave radiation depends on air temperature, as well as on absorption and emission coefficients for each single air layer. The actual absorption and emission coefficients of air depends on the water content but also on gases like carbon dioxide CO_2 and ozone O_3. Yet, only absorption due to water (i.e. VP) is taken into account (Paltridge and Platt 1976, Gross 1991) because of the complex absorptive relationships as well as the lack of information about the vertical distribution of carbon dioxide CO_2 and ozone O_3. Hence, the long-wave atmospheric radiation at a height z, if not modified by vegetation, can be approximated after integration for n single layers (Paltridge and Platt 1976) by:

$$R^{\downarrow}_{lw(z)} = \sum_{n=1}^{N} \sigma_B T^4(n) \left[\varepsilon_n(l + \Delta l) - \varepsilon_n(l)\right] \quad (3.3)$$

where *l* is the water content in the layer between the height *z* and the lower layer *n*, ε_n is the emissivity of a layer *n and T* is the absolute temperature.

The short-wave radiation fluxes at the model boundary R^*_{sw} are calculated with the integration of the radiation intensity of the sun I_0 in the wavelength range of λ = 0.29 μm to λ = 4.0μm.

$$R^*_{sw} = \int_{0.29}^{4.0} I_0(\lambda) exp\{-\alpha_R(\lambda)m + \alpha_M(\lambda)m\} d\lambda \quad (3.4)$$

I_0 is available from tables (Houghton 1977). The optical mass *m* is a function of the solar height *h*, the Rayleigh scattering (i.e. $\alpha_R = 0.00816\ \lambda^{-4}$) and Mies scattering ($\alpha_M = \lambda^{-1.3} \beta_{tr}$). The absolute amount of direct short-wave radiation at the model boundary $R^0_{sw,dir}$ is obtained after the deduction of the energy quantity absorbed $R_{sw,abs}$ by the water contained in the atmosphere after Liljequist (1979), namely:

$$R^0_{sw,dir} = R^*_{sw} - R_{sw,abs} = R^*_{sw} - (70 + 2.8VP_{2m} \cdot m) \quad (3.5)$$

The short-wave diffuse radiation $R^0_{sw,dif}$ for cloudless sky conditions depends on the direct solar radiation flux and the sun height ϕ and is estimated after Brown and Isfält, (1974):

$$R^0_{sw,dif} = f\left(R^0_{sw,dir}, \emptyset\right) \quad (3.6)$$

For cloudy sky conditions, the direct solar radiation $R^0_{sw,dir}$ is reduced according to Taesler and Anderson (1984).

The ground surface temperature is calculated by solving the energy balance of the surface:

$$R_{sw,net} + R_{lw,net} - G_0 - H_0 - LE_0 = 0 \quad (3.7)$$

where $R_{sw,net}$ is the net short-wave radiation received by the surface, $R_{lw,net}$ is the net long-wave radiation, G is the soil heat flux, H_0 and LE_0 are the sensible and latent turbulent heat flux, respectively. The calculation of $R_{lw,net}$ is complex and includes the effects of buildings and vegetation, which could be studied in further detail in software documentations (e.g. Bruse 2004). This is particularly relevant for determining courtyard surface temperatures, necessary for evaluating thermal comfort in courtyard.

Similar to the ground surface, the energy balance of a wall or roof surface is given by:

$$R_{sw,net} + R^{w,r}_{lw,net} - H_{w,r} - Q_{w,r} = 0 \quad (3.8)$$

where H_w and $Q_{w,r}$ are the turbulent sensible heat flux and the heat flux through the roof or wall, respectively. $R_{sw,net}$ and $R^{w,r}_{lw,net}$ are net short-wave and long-wave radiation fluxes, the equations of which can be derived from the literature (e.g. Koenigsberger et al. 1973, Markus and Morris 1980).

3.2.2. The human-biometeorological dimension

A discussion of the importance of T_{mrt} for thermal comfort issues and the difficulty related to its determination was presented in section 2.2. In this respect, ENVI-Met gives a good approximation of T_{mrt} at yard level, which is expressed for each grid point *(z)* as follows (Bruse 1999):

$$T_{mrt} = \left[\frac{1}{\sigma_B}\left(E_t(z) + \frac{\alpha_k}{\varepsilon_p}\left(D_t(z) + I_t(z)\right)\right)\right]^{0.25} \quad (3.9)$$

The surrounding environment in the courtyard consists of the building surfaces, the free atmosphere (sky) and the ground surface. All radiation fluxes, i.e. direct irradiance $I_t(z)$, diffuse and diffusely-reflected solar radiation $D_t(z)$ as well as the total long-wave radiation fluxes $E_t(z)$ from the atmosphere, ground and walls, are taken into account by ENVI-met.

At street level, $E_t(z)$ is assumed to originate as 50 % from the upper hemisphere (sky and buildings) and 50 % from the ground. This is only valid at street level and further approximation is performed for higher grids.

3.2.3. Boundary conditions and course of a simulation

Fig. 3.1, shown previously, illustrates the following description. The equations used in the boundary model are a 1D simplified form of those used in the 3D model with some parameterisations when necessary. The vertical wind inflow profile up to a height of 2500 m is calculated with the 1D model by applying a logarithmic law, based on the input values of the horizontal wind (u, v) at 10 m height above ground and on the roughness length z_0.

The initial temperature (θ_{start}) given as an input parameter at a height of 2500 m is set to the whole vertical profile assuming start conditions of neutrality. A vertical gradient forms if the initial surface temperature differs from the initial air temperature. The surface temperature is provided to the 1D model by the soil sub-model, and is calculated on the basis of three input values of soil temperatures and soil humidity. The air humidity profile is linear and is calculated by means of input values at 2500 m i.e. $\bar{q}_{2500m}$ and the relative humidity *RH* at 2 m. Turbulence quantities E and ε are constant at 2500 m and are function of the local friction velocity u* (a reference wind velocity applied to motion near the ground where the shearing stress is often assumed to be independent of height and proportional to the square of the mean velocity). The surface temperature and humidity are provided by the 3D model as mean values of the nesting area related values.

The initialisation of the 1D model is run during a period of 8 hours with a time step of Δt = *1s* until the interactions between all start values reach a steady state, i.e. $dK_m/dt < 10^{-3}m^2 \cdot s^{-2}$. The atmospheric equations are solved by integration of the variables in the following order: $\bar{u}, \bar{v}, \bar{\theta}, \bar{q}$, *E* and ε, and the exchange coefficients K_m, K_h, and K_q.

Start values at the *inflow boundary* of the 3D model are provided by the 1D boundary model as a vertical profile. The transition from 1D to 3D schemes needs an adjustment in non-homogenous urban surroundings. This is solved by the use of the 3D nesting area. On the horizontal boundary, homogeneity is assumed. Wall and roof temperatures are calculated at all physical boundaries in the model area. The wind speed components at building grids are set following a *no-slip* condition i.e. *u* = *v* = *w* = *0*. The wind field is adjusted to the presence of the obstacles gradually during the initializing phase (*diastrophic phase*). At the ground surface (*z* = *0*) and on the walls, E and ε are calculated as a function of u* from the flow components tangential to the surface. It is assumed that no gradient exists between the two last grids close to the outflow border.

The actual 3D simulation includes, in the following order, the calculations of soil parameters (T, η), surface quantities (T_0 , q_0, a_s), radiation update, the update of wind components ($\bar{u}, \bar{v}, \bar{w}$), pressure perturbation p', turbulence quantities E, ε , K_m , K_h , K_q , and air temperature and humidity θ , q. The process is repeated once the 1D model is updated again.

Numerically, all differential equations are approximated using the finite difference method and solved forward-in-time. Time steps adopted vary depending on the quantity to be calculated. The main time step is 10 minutes for the wind flow calculations. Smaller time steps are used for E- ε system to obtain numerically stable solution (3 minutes).

Solar radiation is usually updated in larger time-steps and can be set by the user. To solve the advection-diffusion equation, dynamic pressure is removed from the equations of motion and auxiliary flow components are calculated, these are then corrected by incorporating the dynamic pressure which has been separately defined by means of the Poisson equation (Bruse 2004).

3.3. Empirical validation of ENVI-met

Numerical climate modelling was discussed to be a promising approach for describing the urban microclimate and its underlying processes. However, the simulation tool used in this research, ENVI-met, is a relatively new simulation program without much commercial application up to the present moment and the developers accept that it is still under the process of constant development (ENVI-met website 2008). Therefore, it is advisable to approach this software, like any other new untried tool, with a level of caution. This section addresses the two main concerns about ENVI-met from the viewpoint of this research and tests the software via different methods to evaluate its suitability for the desired purpose.

As mentioned earlier, the two tasks expected from ENVI-met during this study are as follows:

- to predict the air temperature in different locations in a courtyard or a yard;
- and to predict the temperatures observable on the outer face of a wall, facing the courtyard.

In order to validate the performance of the program in the first field (i.e. predicting outdoor air temperature) , a number of ENVI-met simulations were run for, and compared to, the climate conditions that prevailed on the observation day in order to test the ability of the model to simulate the climate conditions of 3 courtyards and their built-up surroundings. These courtyards are situated in the West Park of Loughborough University campus in Loughborough, UK and the data collection has been performed by a small group of researchers, lead by the author of this thesis.

Each courtyard and its surroundings were built up in ENVI-met with a grid resolution of 1 x 1 x 1 m. To increase the accuracy of the near surface climate, the grid box closest to the ground and surrounding walls was further subdivided into five equally thick layers (i.e. $\Delta Z = 0.2$ m). Later boundary conditions were chosen so that downstream conditions were copied to the inflow profile.

The Following section describes the details of the measurements and simulations performed on one of the courtyards and also present the results for the rest of the cases.

3.3.1. Courtyard microclimate: Observations

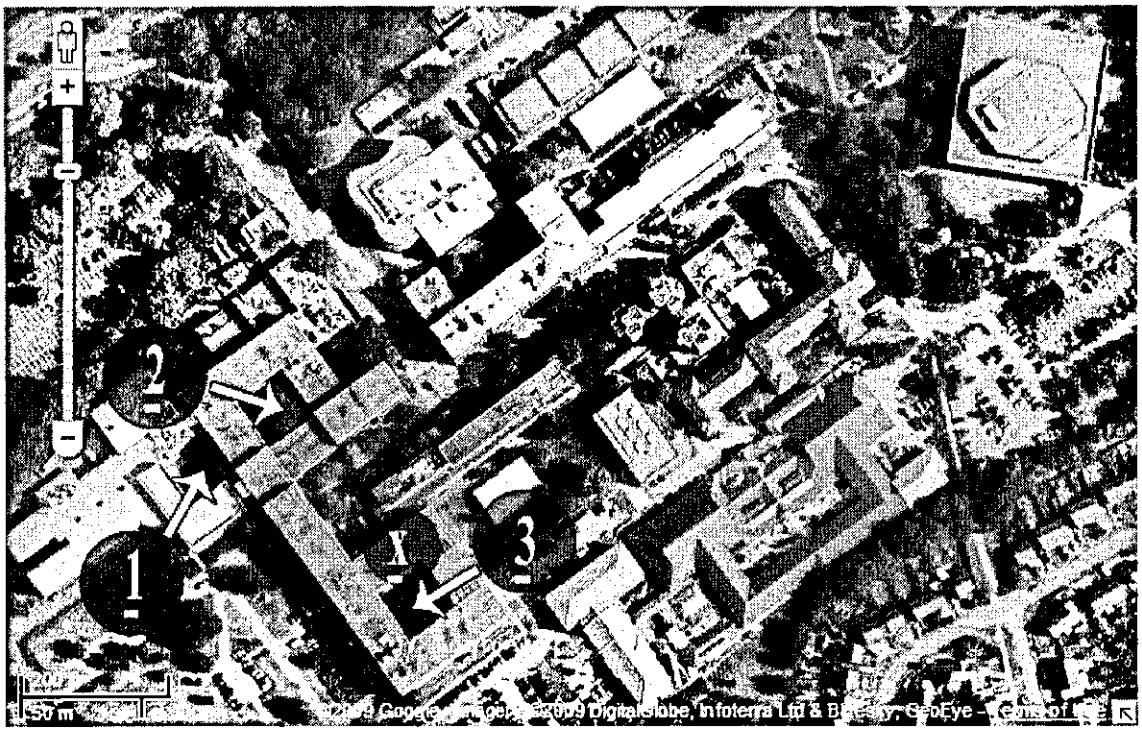


Figure 3.2 The three observed courtyards: 1) Aeronautical Engineering Department; 2) Chemical Engineering Department; 3) Physics Department x) Physics Department weather station (Satellite image from Google Maps UK 2009)

Three Courtyards (1 to 3 in Figure 3.2) were selected to be observed for a 24 hours period during a typical summer day in Loughborough, UK. The values for air temperature in the courtyards were to be measured in 3 hour intervals and compared to the ones predicted by ENVI-met for a similar setting. All selected courtyards were of similar size and orientation and situated close to each other in order to make the results more comparable and easier to form a conclusion. To be able to distinguish other factors affecting the air temperature, values of relative humidity and wind speed were also measured and shade patterns were recorded. Observed factors were also compared to the values measured by the experimental weather station (marked by white X in Figure 3.2) on the rooftop of one of the surrounding buildings in order to investigate the modifying effect of courtyards on outdoor weather.

I) Observation procedure

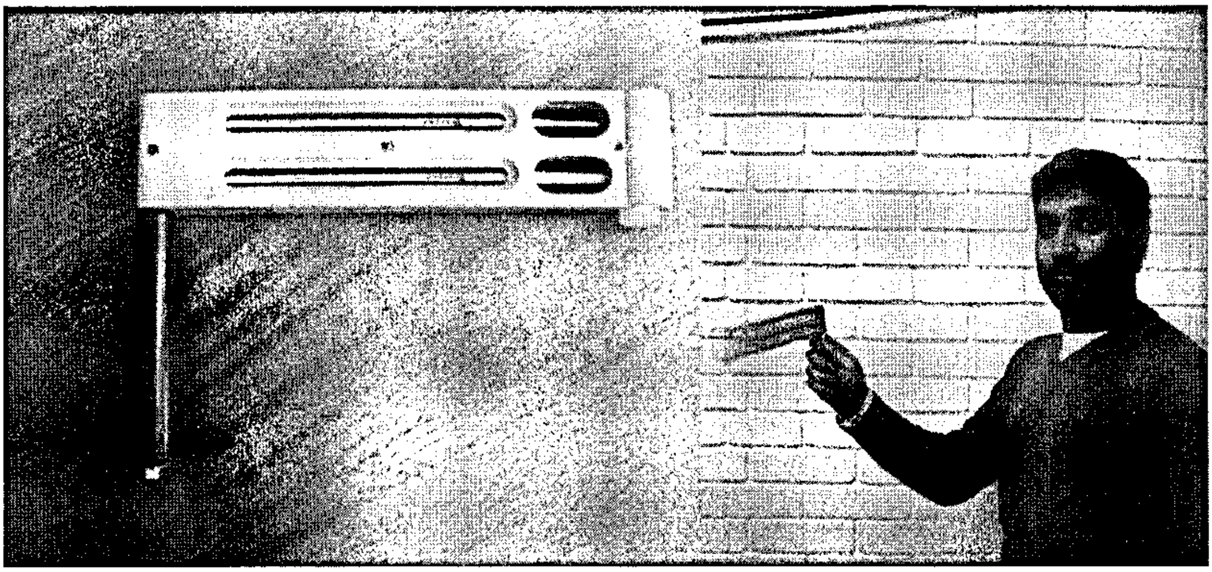


Figure 3.3 Whirling hygrometer for measuring dry bulb and wet bulb themperatures

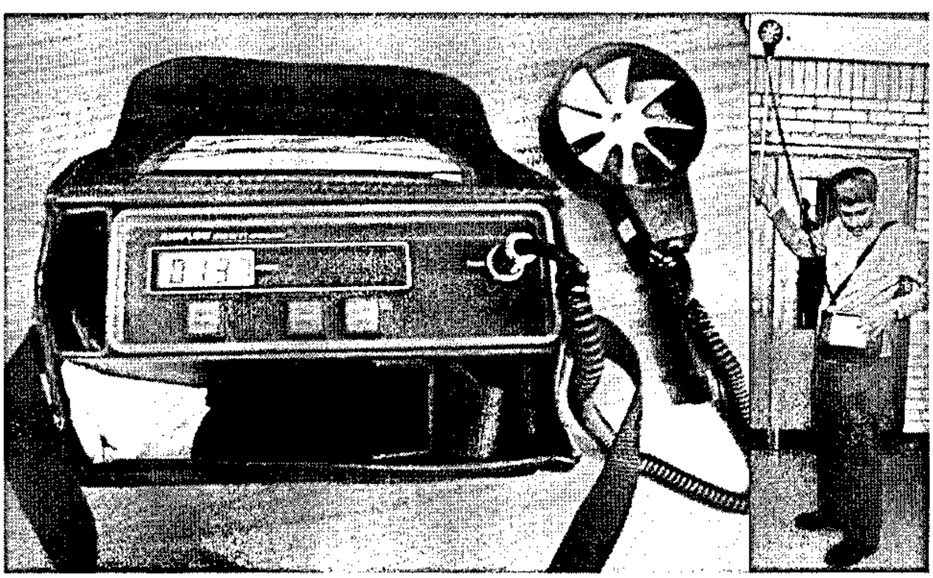


Figure 3.4 Digital anemometer for measuring wind speed

The observations were conducted through a full 24 hour period starting from midday of the 29th of June, 2006. The group measured dry bulb and wet bulb temperatures (by a simple whirling hygrometer (Figure 3.3) and vertical and horizontal air speed (by a digital handheld anemometer; Figure 3.4) at 5 points within each courtyard (the middle point and at points approximately 1.5m from each corner; e.g. Figure 3.5) and at two different heights (approximately 0.2m and 2.5m).

Air temperature and wind speed in each courtyard were calculated by averaging between the 5 values measured at each observation time. The air humidity were extracted from the standard table accompanying the whirling hygrometer, the contents of which are presented in table 3.1)

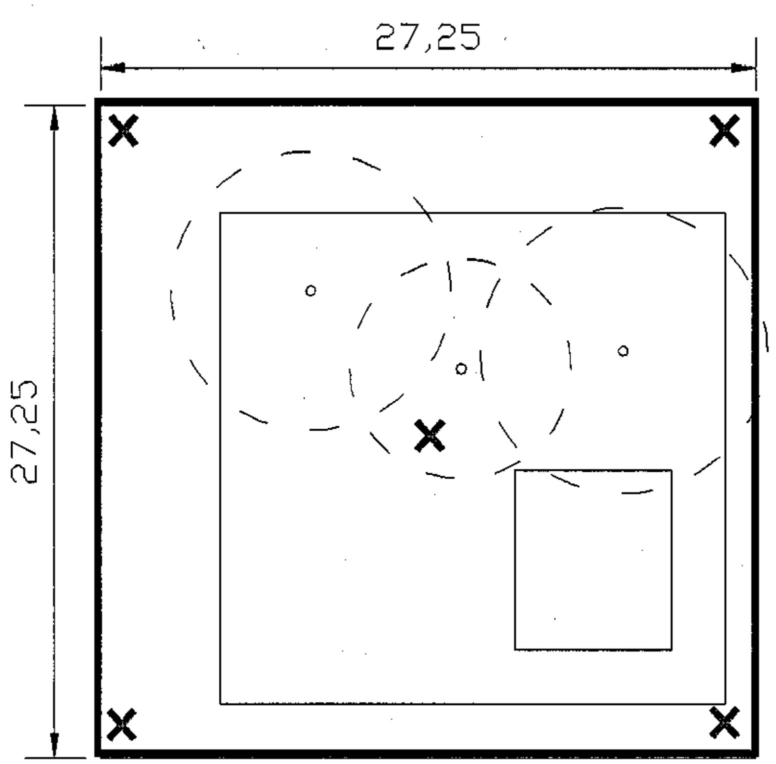


Figure 3.5 Measurement points in courtyard 2

Dry bulb temp., °C	Dry-bulb temperature minus wet-bulb temperature (Dry-bulb depression), °C														
	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20
2	84	68	52	37	22	8									
4	85	71	57	43	29	16	3								
6	86	73	60	48	35	24	11								
8	87	75	63	51	40	29	19	8							
10	88	77	66	55	44	34	24	15	6						
12	89	78	68	58	48	39	29	21	12						
14	90	79	70	60	51	42	34	26	18	10					
16	90	81	71	63	54	46	38	30	23	15					
18	91	82	73	65	57	49	41	34	27	20	7				
20	91	83	74	66	59	51	44	37	31	24	12				
22	92	83	76	68	61	54	47	40	34	28	17	6			
24	92	84	77	69	62	56	49	43	37	31	20	10			
26	92	85	78	71	64	58	51	46	40	34	24	14	5		
28	93	85	78	72	65	59	53	48	42	37	27	18	9		
30	93	86	79	73	67	61	55	50	44	39	30	21	13	5	
32	93	86	80	74	68	62	57	51	46	41	32	24	16	9	
34	93	87	81	75	69	63	58	53	48	43	35	26	19	12	5
36	94	87	81	75	70	64	59	54	50	45	37	29	21	15	8
38	94	88	82	76	71	66	61	56	51	47	39	31	24	17	11

Table 3.1 Relative humidity (%) based on dry-bulb and wet-bulb temperatures

II) Observation results

Although, the air movements measured during the 24 hours of observation, both in the courtyard and in the weather station on the rooftop, were of a low speed (from 0.15 to 1 m/s), in general, the courtyards tend to prove calmer than the general outdoor (up to 0.6 m/s lower wind speed) during slightly more turbulent times. In contrast, when the outdoor air velocity falls below 0.3 m/s, the average wind speed inside courtyards is up to 0.3 m/s higher (Figure 3.6).

Values recorded for relative humidity, apart from around the time of the watering of the trees and the lawn in the courtyards (e.g. at 18.00 hrs in courtyard 3), show a

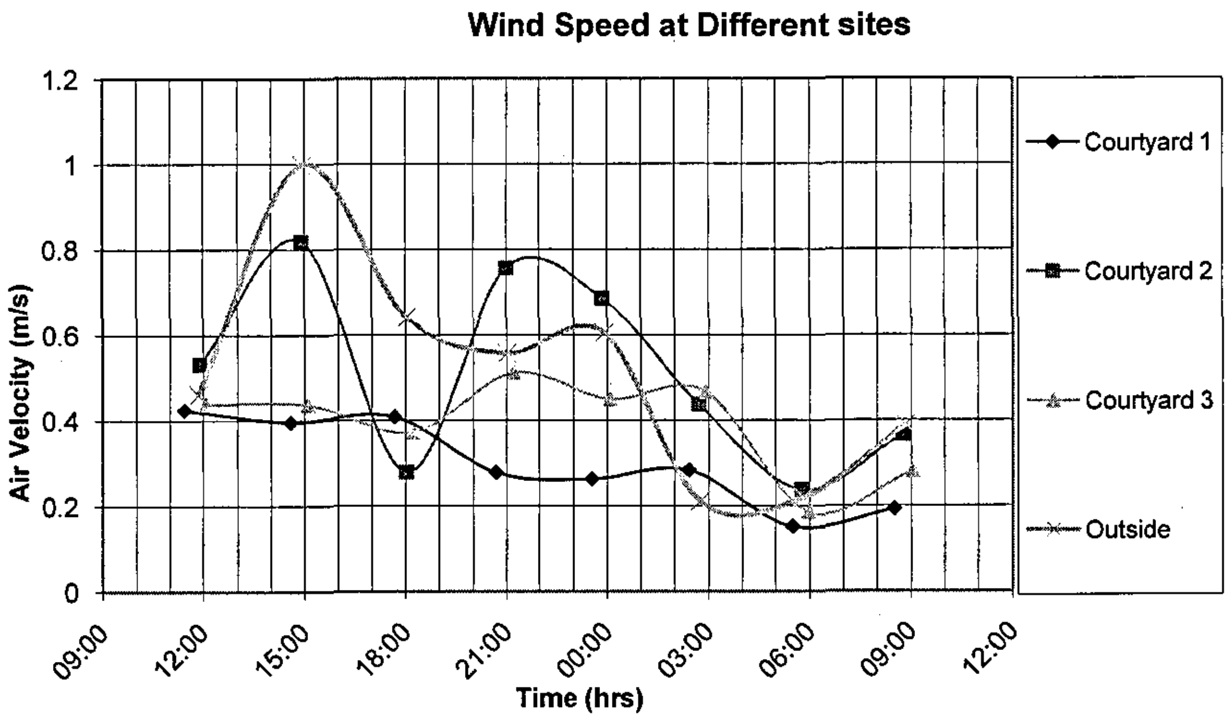


Figure 3.6 average air velocity inside courtyards

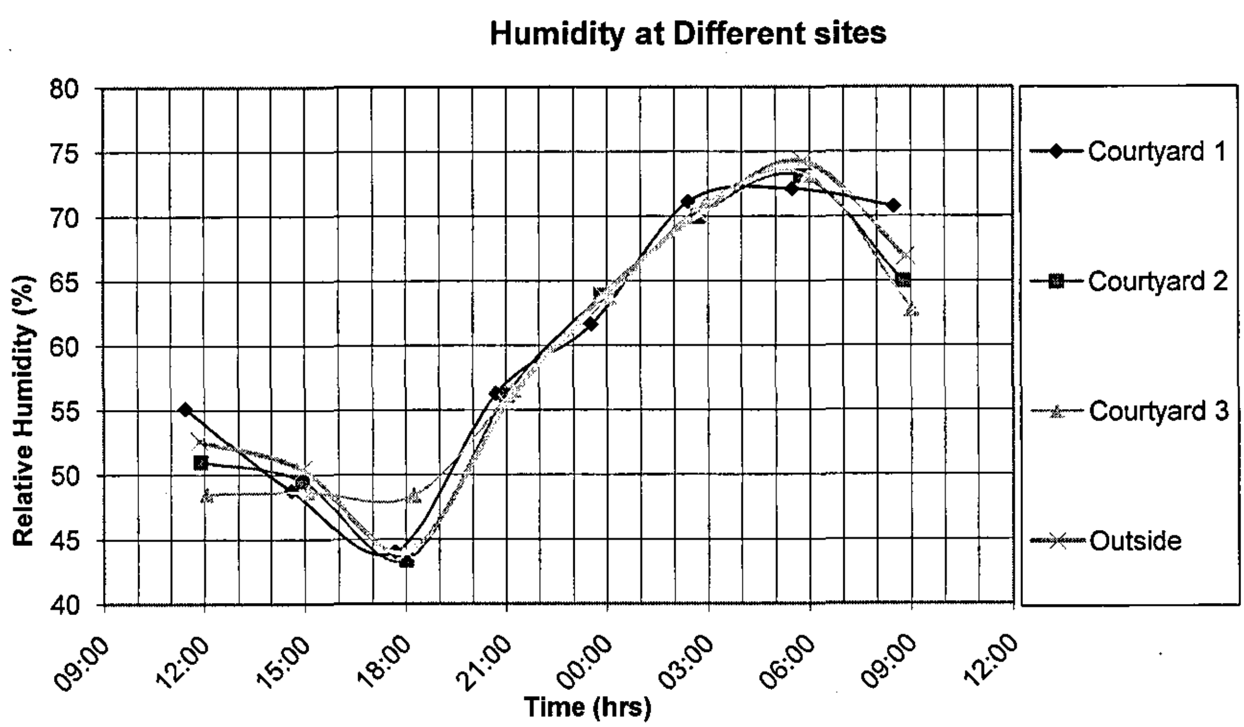


Figure 3.7 Average relative humidity inside courtyards

maximum of 2 to 3% difference from the humidity outside. This is not enough to base a conclusion on the effect of courtyards on relative humidity (Figure 3.7).

Air temperatures in all courtyards prove to be lower than the air temperature outside (by up to 2 ºK) during the warmer times of afternoon (from midday to sunset). Through the night, this difference is gradually reduced and in the early hours of morning becomes very insignificant (Figure 3.8). The same pattern is also noticed when considering each of the 5 measurement points in each courtyard separately. This is in consistence with the results of some previous studies on microclimatic effect of courtyards, some of which were introduced in literature review (Chapter 2).The latter category of measured values (air temperatures) is of main concern in this thesis and, therefore, will be subject of more emphasis when compared to the values predicted by ENVI-met for similar settings.

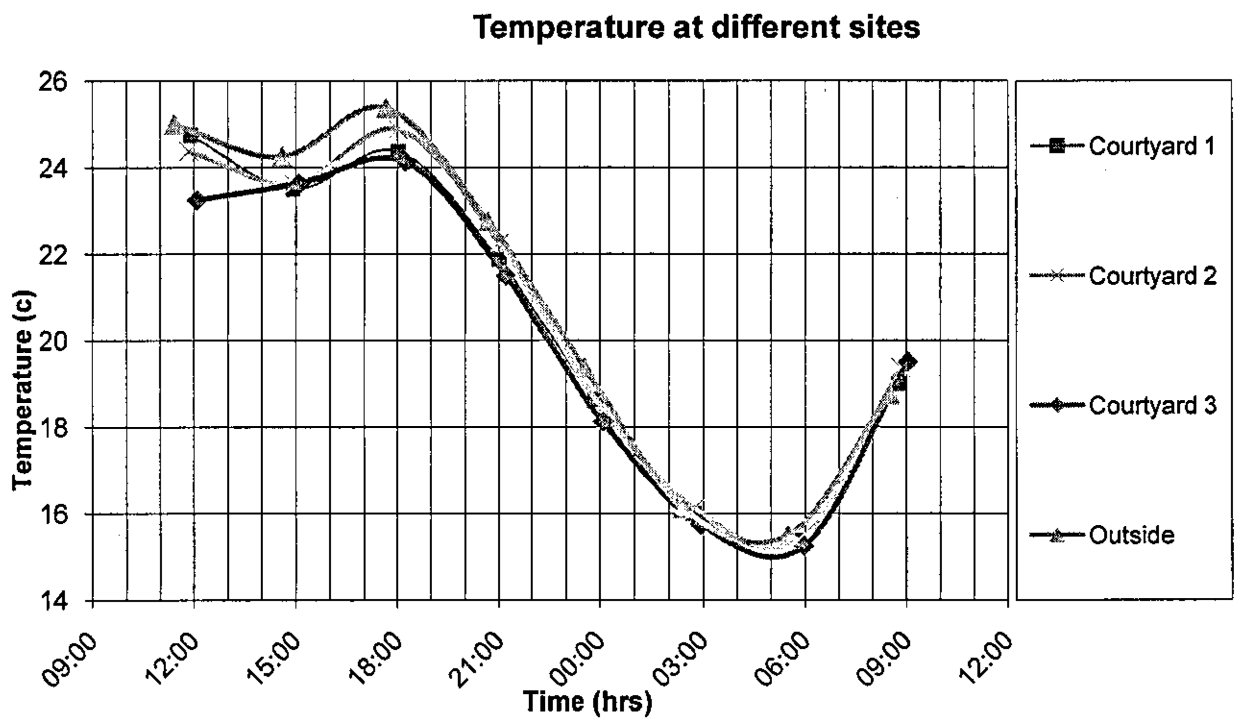


Figure 3.8 Average air temperature inside courtyards

3.3.2. Courtyard microclimate: Simulations

At this stage the climatic and structural environment of the observed case is to be modeled in ENVI-met and the values for average air temperature are to be simulated for a period of 24 hours. The predicted values will then be compared to the ones directly measured on site and similarities and differences will be discussed to form a base for determining the validity of ENVI-met for outdoor simulations sought by this research.

I) Simulation settings

Clearly the accuracy of simulation results is highly dependent on the accuracy of the input data and, therefore, maximum effort has been put into creating a setting as close as possible to the one at the time of observation. In addition to the standard program settings (described in 3.2), structural features like the size of the courtyards, the height of the surrounding buildings, the orientation of the buildings (+36° from East-West axis), number, location, size and density of the trees inside courtyards and colour and material of surrounding surfaces were defined according to the existing conditions at the time of observations (Figure 3.9). It should be mentioned here that Figure 3.9 only shows the major 10X10 m grid of the settings. The actual simulation grid is a fine 1X1 m grid to enable a more detailed reading of the changes in air temperatures

. Furthermore, the climatic data gathered on the rooftop of one of buildings (Figure 3.2) in addition to the horizontal and vertical angles of the apparent position of the sun (a graphical representation of which is shown in Figure 3.10) were used to define the climatic conditions of the simulation.

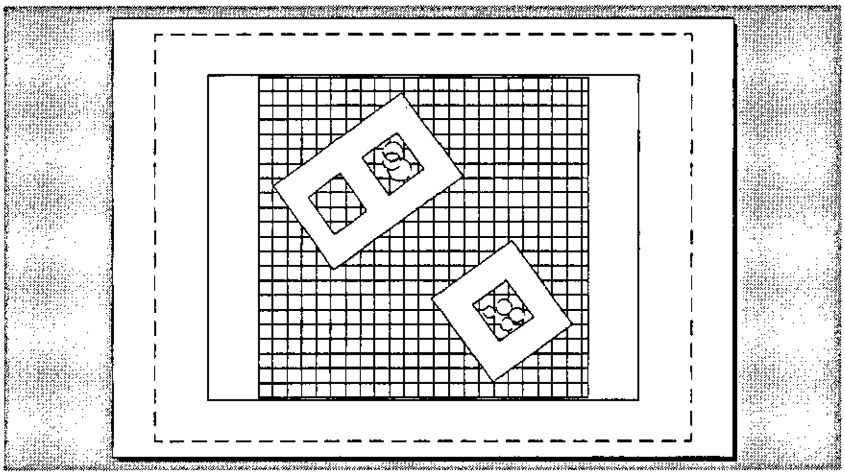


Figure 3.9 Surrounding settings as defined for ENVI-met

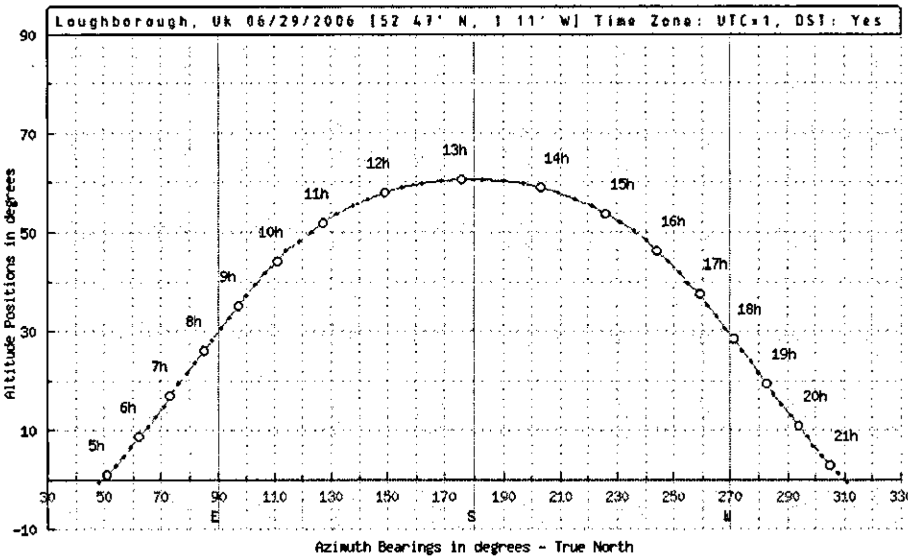


Figure 3.10 apparent position of the sun during the first day of observations (www.sunposition.info 2006)

A number of simplifications had to be made during the modeling process due to the restrictions by the program and/or limitations in the data gathered:

- As exhibited earlier, the wind speeds at the time of observation were very low (always below 1m/s) and, consequently, the effects of them on the conditions and results of the current simulations are not expected to be significant. Therefore, to avoid the complications caused by varying air speeds, the wind speed during the period of simulations was chosen as a constant value of 0.5 m/s in the main wind direction recorded on the day (South-West).

- Although the outer surface of the walls surrounding courtyards consisted of different materials (brick, glass, exposed concrete etc) with different colours, the restrictions dictated by the program made it necessary to use a homogenous surface with characteristics similar to the ones of brick (which composes the highest percentage of the surfaces in all three courtyards).
- The ground surface was also assumed to be uniform for the same reason and short grass, for being, in reality, the major cover of the ground surface in the area of observation (Figure 3.2), was chosen as this uniform surface.
- Apart from the three courtyards and buildings surrounding them, the rest of the neighbouring buildings and plant cover have been replaced by the ground surface defined in the previous paragraph (Figure 3.9). Since the focus is exclusively on the environment inside courtyards, the elements beyond the immediate surroundings of the courtyards could be, practically, considered of no or very little significance in the simulations (figure 3.2).

II) Simulation results

Figure 3.11 shows the average air temperature of the courtyards as predicted by ENVI-met in comparison with those recorded for the surrounding area. The values shown in this diagram are an average between the predicted temperature values for the simulation grids corresponding to the 5 measurement spots in the observation process (e.g. Figure 3.5).

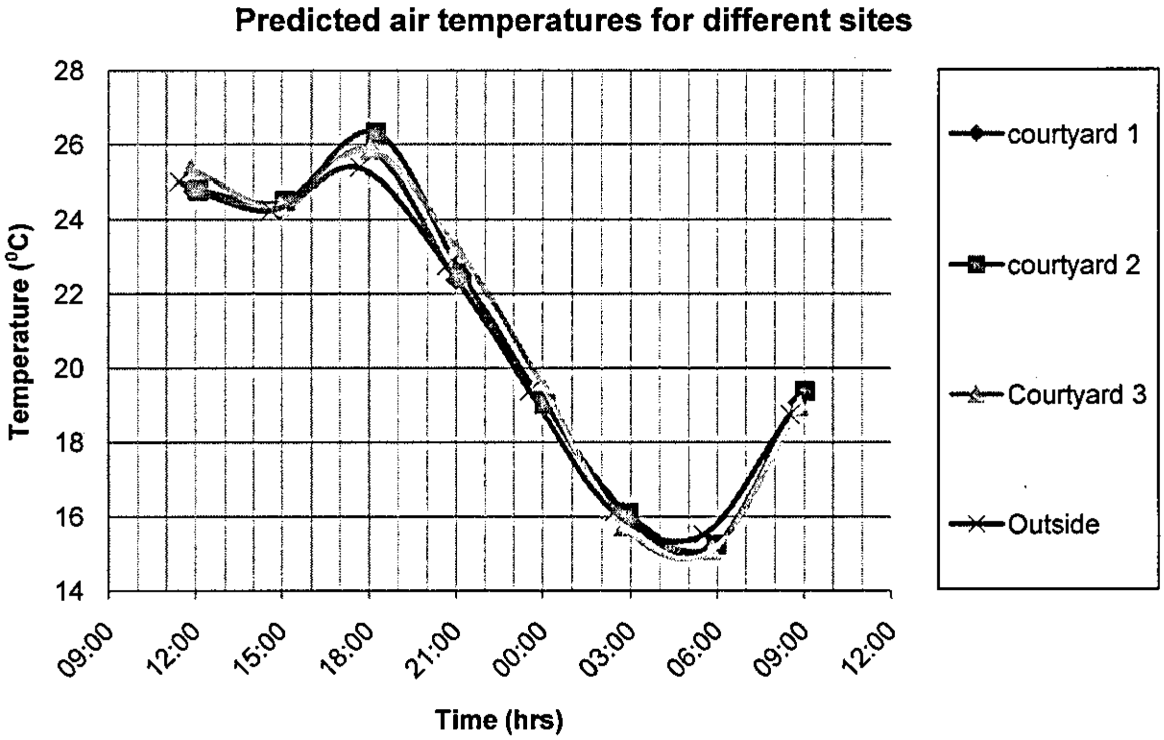


Figure 3.11 Average air temperature of the courtyards as predicted by ENVI-met

It shows a very close relationship between the air temperatures in all three courtyards as well as between the courtyards and the general outdoor. The maximum difference between the predicted values and outside air temperature occurs during the warmest time of the day and is about 1°K, which is less than half of what was recorded during direct observations. More importantly, this difference is in the opposite direction, meaning that unlike what really happened and was measured in the observation stage, ENVI-met predicts a higher temperature in the courtyards in the afternoon and lower temperatures in early morning. This is a concerning inconsistency and needs to be investigated in more depth.

3.3.3. Discussion

To address this concern, the air temperatures observed at each of the 5 measurement stations in each courtyard (e.g. Figure 3.12) were plotted against the temperatures predicted for the corresponding simulation grid in ENVI-met. An example of the results is shown in Figures 3.13 and 3.14.

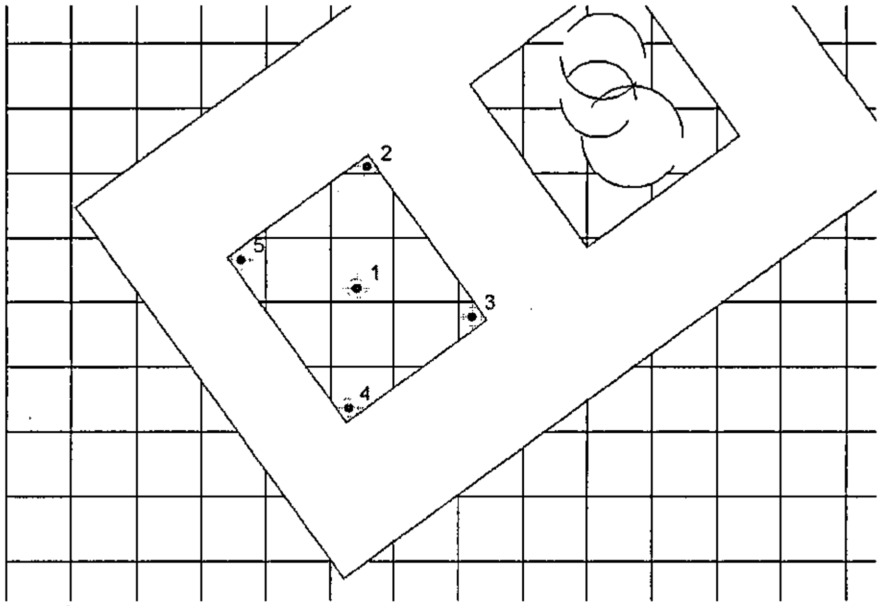


Figure 3.12 Measurement stations in Courtyard 1

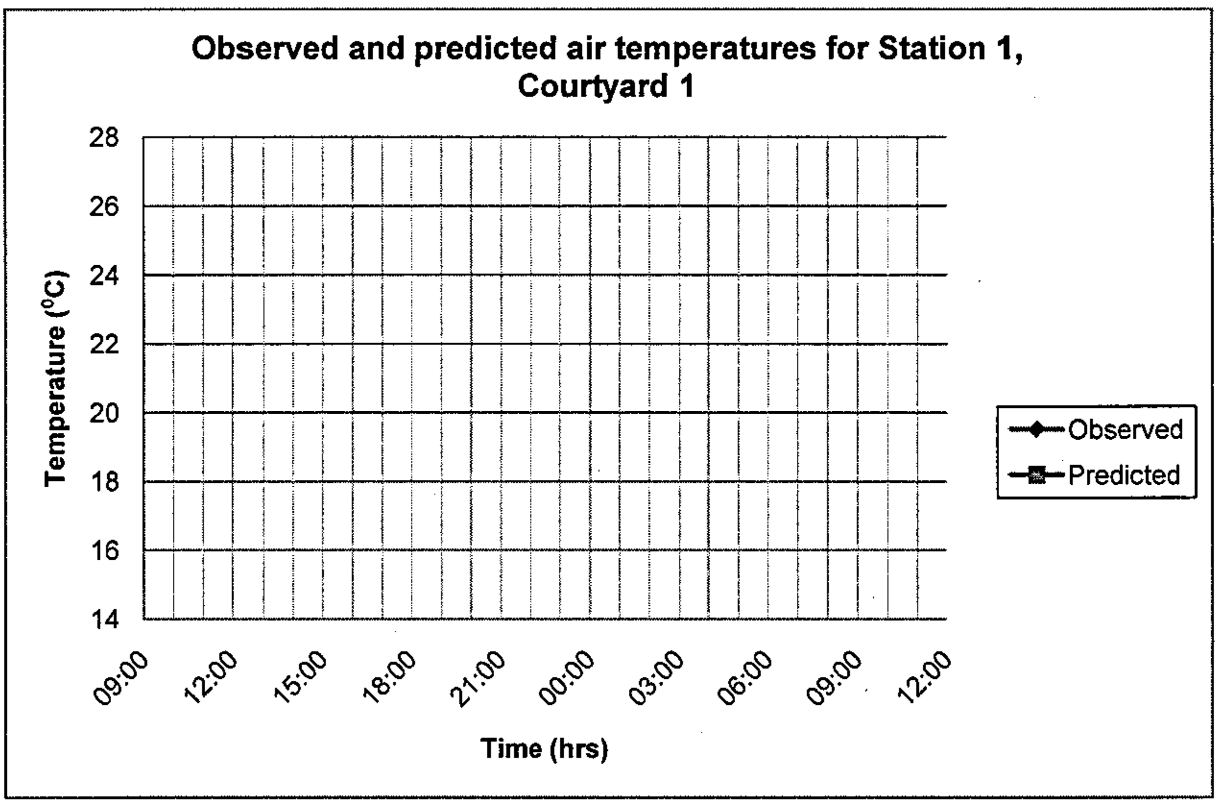


Figure 3.13 Observed and predicted air temperatures for the middle point of one of courtyards

It is clear from the first diagram (Figure 3.13) that ENVI-met predictions for the air temperature at the centre of the courtyard agree very closely with the actual air temperature at that point as directly measured during the period of observation. The difference between the two is never more than 0.5 °K and therefore the divergence observed in the averaged air temperature values cannot be contributed to this point.

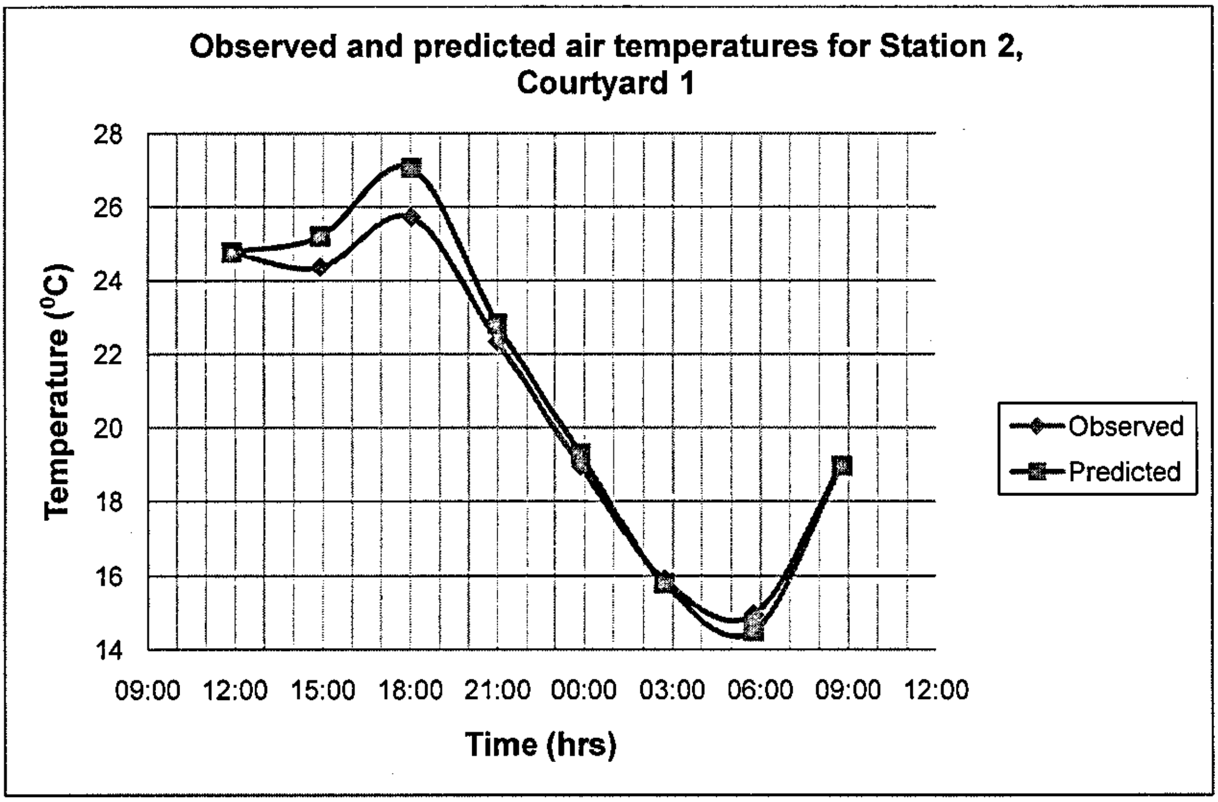


Figure 3.14 Observed and predicted air temperatures for the northern corner of one of courtyards

The observation/simulation point situated at the northern corner of the courtyard (station 2), however, shows higher differences between measured and simulated air temperatures. These differences are visible during day and night. The day-time air temperatures predicted for this station by ENVI-met could be up to 1.5 °K higher than real temperatures (in the afternoon). By observing the other 13 stations, It could be concluded that ENVI-met assumes a faster heat gain (compared to reality) for the corner points when they are in the sun and, in the same way, a faster heat loss when they are in the shade. This could be attributed to a known limitation in ENVI-met in the way it deals with the heat storage in surfaces. Such a limitation has been reported before this by Ali-Toudert (2005) and is a plausible reason for faster changes in the surface temperatures and, consequently in the temperature of the air near those surfaces.

Since, in each courtyard, there are four corner points for each central point, when averaging between the 5, these fluctuations in air temperatures makes the average result invalid. To examine this theory, a second set of average air temperatures is produced, but this time with excluding the squares adjacent to the walls. This average is shown in Figure 3.15 together with the average of observed air temperatures and it proves a very close coherence with actual values. The difference between the two sets is never more than 0.5 degrees, which considering the

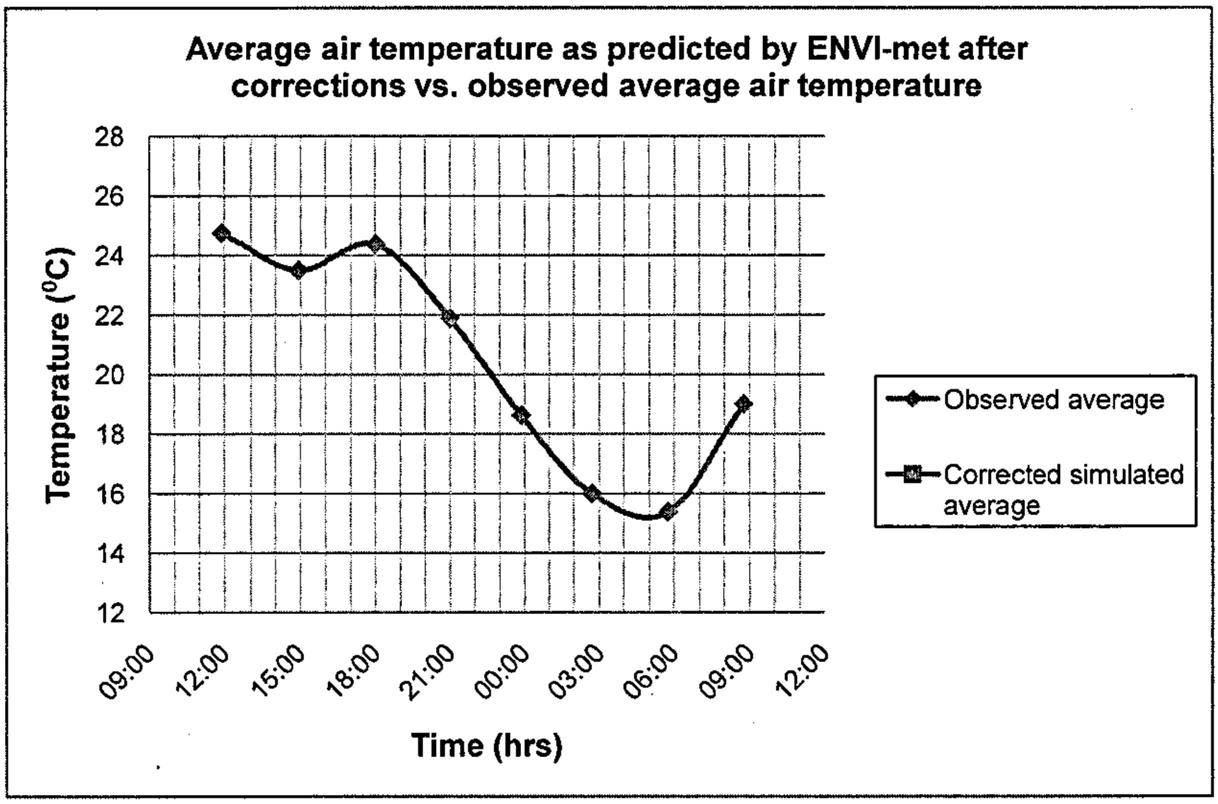


Figure 3.15 comparison between measured average air temperature and simulated average air temperature after excluding the layer of air next to surfaces.

elimination of surrounding squares and also the simplifications described earlier, could be accepted as a good agreement and a validation for the way ENVI-met predicts air temperatures.

3.4. Analytical validation of ENVI-met

As a result of what was presented in the previous section, although the results derived from ENVI-met for air temperatures in the courtyard are, in general, reliable in the scale of the present research, part of these results (i.e. the part related to the edges of the courtyard) cannot be used because of a potential weakness in ENVI-met in calculating the heat storage effect of the walls and, consequently, surface temperatures. Regarding the accuracy of the results given by ENVI-met for simulated courtyards, daily surface temperatures could be divided in two main categories:

- *Diurnal surface temperatures*

The difference observed between real day-time temperatures of the air close to the walls of a courtyard as measured directly and the same set of temperatures as predicted by ENVI-met is far greater than any acceptable level (e.g. Figure 3.14). This fact in addition to previous studies mentioning the lack of a reliable approach in ENVI-met for predicting surface temperatures (e.g. Ali-Toudert 2005), leads to the conclusion that to correct this divergence, the best advisable way is to use a second tool with more validation in this area and link that tool with ENVI-met. Next chapter will present a detailed approach to this linking as part of a broader integration of ENVI-met with an indoor simulation program named TRNSYS.

- *Nocturnal surface temperatures*

The two-program approach mentioned above could also be used for any night-time simulation of surface temperatures and, in fact, that is exactly how the surface temperatures will be dealt with in following two chapters. However, as seen in Figure 3.14 and repeated in other similar simulations, the difference between observed and simulated air temperatures near the walls, during the night, is in a reasonably small range and this small difference could be attributed to the simplifications made in the simulation process. Therefore, although neither day-time nor night-time surface temperatures offered by ENVI-met will be used in this research, in this section an attempt will be made to assess the accuracy of ENVI-met in predicting surface temperatures during night. The analytical method presented here intends to provide an accurate theoretical basis for validating the software in regards to the present problem.

3.4.1. Defining the problem

An analytical solution is needed for determining the surface temperatures of the walls surrounding a courtyard in a steady state (i.e. the total amounts of heat gained and lost by the courtyard are equal) based on the heat exchanges on its surrounding surfaces. These surfaces are defined as follows:

- Sky: A fictitious 2D black body (with zero reflection) lying on the top surface of the courtyard. Sky temperature (T_s) is taken as known as it can be calculated independently from the conditions within courtyard (Garg and Prakash 2000).
- Floor: A diffuse grey object, forming the bottom surface of the courtyard. Methods for calculating ground temperature are well documented (e.g.

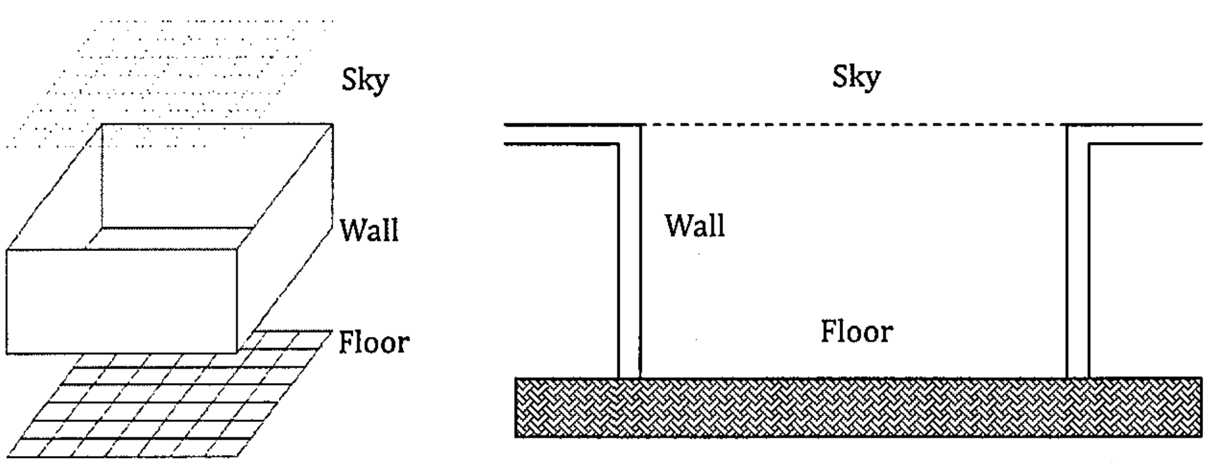


Figure 3.16 Surfaces surrounding the courtyard in isometric view (left) and cross section view (right)

Titanova et al 1996) and will be adopted in this research. The temperature determined by one of these methods (T_f) is taken as one of the known parameters in the current analytical model.

- Wall: A 3D diffuse grey surface surrounding all vertical sides of the courtyard with the assumption that all characteristics of the four surrounding walls, including the air temperatures on both sides of the walls, are identical on all four surrounding sides. The temperature of this surface (the surface of the wall facing the courtyard) is shown as T_w and is the unknown of the problem defined by this model.

3.4.2. Basic equations

The analytical model presented here, considers all three methods of heat transfer between these different surfaces and through the surrounding walls. The basis of this approach is the simple idea of energy balance in a wall:

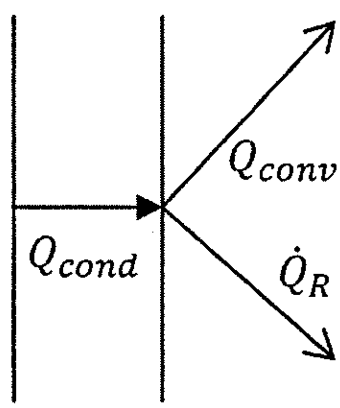


Figure 3.17 Enegy balance on the wall surface

$$Q_{cond} = Q_{conv} + \dot{Q}_R \tag{3.10}$$

Where,

Q_{cond} is the heat loss through the conduction in the wall;

Q_{conv}, the heat loss from the surface of the wall to the outdoor air through convection;

and $\dot{Q}_R$, the net amount of heat radiated by the outer surface of the wall to other surrounding surfaces.

These three factors have been discussed in much detail in reference books. Equations presented here are from "Heat Transfer: A Practical Approach" by Yunus A. Çengel (2003):

I) $$Q_{cond} = \frac{A_w(T_r - T_w)}{R_w} \quad (3.11)$$

In which,

A_w is surface of the wall in m^2;

T_r is surface temperature of the wall on the inner surface in $°K$;

T_w is surface temperature of the wall on the outer surface in $°K$;

and R_w is thermal resistance of the wall in m^2K/W.

II) $$Q_{conv} = h_c A_w (T_w - T_a) \quad (3.12)$$

Where,

h_c is convective coefficient of the wall in $W/_{m^2 °C}$;

and T_a is temperature of the layer of outside air next to the wall in $°K$.

III) $\dot{Q}_R$ is diffuse radiosity (i.e. net amount of emitted and reflected radiation) of the wall and, by definition, is equal to the integral of the hemispherical spectral radiosity (Jλ) over the spectrum:

$$\dot{Q}_R = \int_0^{\infty} J_\lambda(\lambda)d\lambda \tag{3.13}$$

Where, J_λ is equal to integral over the hemispherical solid angle of the sum of emitted and reflected radiant intensities. In the case of the walls surrounding the courtyard in this model, since the only two surfaces emitting and receiving radiated heat to and from the wall enclose are floor and sky surfaces, $\dot{Q}_R$ will be:

$$\dot{Q}_R = A_w\left(F_{ws}(J_w - J_s) + F_{wf}(J_w - J_f)\right) \tag{3.14}$$

Where,

F_{ws} and F_{wf} are sky and floor view factors for the enclosure wall, J_s, J_w and J_f are equal to total radiative energy leaving the sky, wall and floor surface per unit area.

Equation (3.10) can be rewritten by replacing its components with their equals from equations (3.11), (3.12) and (3.14):

$$\frac{T_r - T_w}{R_w} = h_c(T_w - T_a) + \left(F_{ws}(J_w - J_s) + F_{wf}(J_w - J_f)\right) \tag{3.15}$$

On the other hand, when considering radiative heat exchanges within the courtyard in the model, since all exchanges happen between three objects: the top surface (sky), which is a black body, the bottom surface (floor) and the surrounding surface (wall), which are both diffuse grey objects, the radiosity equation (3.13) could be rewritten and rearranged for each surface as follows:

$$\sigma T_f^{\ 4} = J_f + \frac{1-\varepsilon_f}{\varepsilon_f}\left(F_{fs}(J_f - J_s) + F_{fw}(J_f - J_w)\right) \tag{3.16}$$

$$\sigma T_w^{\ 4} = J_w + \frac{1-\varepsilon_w}{\varepsilon_w}\left(F_{ws}(J_w - J_s) + F_{wf}(J_w - J_f)\right) \tag{3.17}$$

$$\sigma T_s^{\ 4} = J_s \tag{3.18}$$

the parameters in which are recognised as follows:

- σ (Stefan-Boltzmann's constant = 5.67×10^{-8})
- T_s (Sky temperature in °K)
- T_f (Floor temperature in°K)
- ε_w (Emissivity of the surrounding wall)
- ε_f (Emissivity of the floor)
- ε_s (Emissivity of the sky = 1)
- F_{fs} (Sky view factor for the floor)
- F_{fw} (Wall view factor for the floor)

3.4.3. Derivation of the analytical model

- *Plan*

A model is needed for calculating T_w by using the fundamental equations described in (3.4.2). Apart from J_w and J_f (that are defined by T_w), all other parameters introduced are either constant numbers (e.g. σ), calculable by models independent from the courtyard heat exchange system (e.g. T_s and T_f) or defined in the specific case (e.g. emissivity and view factors of each surface).

To distinct T_w as the only unknown of the problem, first J_w and J_f must be extracted from (3.16) and (3.17) as functions for T_w, then T_w can be solved from equation (3.15).

- *Step one: Defining J_f as a function of T_w*

Multiplying both sides of equation (3.16) by ε_f gives:

$$\sigma T_f{}^4 \varepsilon_f = J_f \varepsilon_f + F_{fs} J_f - F_{fs} J_s + F_{fw} J_f - F_{fw} J_w - \varepsilon_f F_{fs} J_f + \varepsilon_f F_{fs} J_s - \varepsilon_f F_{fw} J_f + \varepsilon_f F_{fw} J_w \tag{3.19}$$

and therefore,

$$\sigma T_f{}^4 \varepsilon_f = J_f(\varepsilon_f + F_{fs} + F_{fw} - \varepsilon_f F_{fs} - \varepsilon_f F_{fw}) + \varepsilon_f F_{fs} J_s + \varepsilon_f F_{fw} J_w - F_{fs} J_s - F_{fw} J_w \tag{3.20}$$

So, J_f can be defined as:

$$J_f = \frac{\sigma T_f{}^4 \varepsilon_4 + F_{fs} J_s + F_{fw} J_w - \varepsilon_f F_{fs} J_s - \varepsilon_f F_{fw} J_w}{\varepsilon_f + F_{fs} + F_{fw} - \varepsilon_f F_{fs} - \varepsilon_f F_{fw}} \tag{3.21}$$

or:

$$J_f = \frac{\sigma T_f{}^4 \varepsilon_f + (1 - \varepsilon_f)(F_{fs} J_s + F_{fw} J_w)}{\varepsilon_f + (1 - \varepsilon_f)(F_{fs} + F_{fw})} \tag{3.22}$$

and since $F_{fs} + F_{fw} = 1$, therefore:

$$\boxed{J_f = \sigma T_f{}^4 \varepsilon_f + (1 - \varepsilon_f)(F_{fs} J_s + F_{fw} J_w)} \tag{3.23}$$

By defining these two new factors:

$$\tau_f = \sigma T_f{}^4 \varepsilon_f$$

$$\acute{\varepsilon}_f = 1 - \varepsilon_f$$

equation (3.23) could be re-arranged as:

$$\boxed{J_f = \tau_f + \acute{\varepsilon}_f\left(F_{fs}J_s + F_{fw}J_w\right)} \tag{3.24}$$

- *Step 2: Defining J_w as a function of T_w:*

The two Sides of equation (3.16) can also be multiplied by ε_w:

$$\sigma T_w{}^4\varepsilon_w = J_w\varepsilon_w + (1-\varepsilon_w)\left(F_{ws}(J_w - J_s) + F_{wf}(J_w - J_f)\right) \tag{3.25}$$

And if:

$$\tau_w = \sigma T_w{}^4\varepsilon_w$$

$$\acute{\varepsilon}_w = 1 - \varepsilon_w$$

Then:

$$\tau_w = J_w\varepsilon_w + \acute{\varepsilon}_w\left(F_{ws}(J_w - J_s) + F_{wf}(J_w - J_f)\right) \tag{3.26}$$

By replacing J_f by its equal from (3.24):

$$\tau_w = J_w\varepsilon_w + \acute{\varepsilon}_w\left(F_{ws}(J_w - J_s) + F_{wf}\left(J_w - \tau_f - \acute{\varepsilon}_f\left(F_{fs}J_s + F_{fw}J_w\right)\right)\right) \tag{3.27}$$

which can be rearranged as:

$$\tau_w = J_w\varepsilon_w + \acute{\varepsilon}_w F_{ws}J_w - \acute{\varepsilon}_w F_{ws}J_s + \acute{\varepsilon}_w F_{wf}J_w - \acute{\varepsilon}_w F_{wf}\tau_f - \acute{\varepsilon}_w F_{wf}\acute{\varepsilon}_f F_{fs}J_s - \acute{\varepsilon}_w F_{wf}\acute{\varepsilon}_f F_{fw}J_w \tag{3.28}$$

or:

$$\tau_w = J_w\left(\varepsilon_w + \acute{\varepsilon}_w F_{ws} + \acute{\varepsilon}_w F_{wf} - \acute{\varepsilon}_w F_{wf}\acute{\varepsilon}_f F_{fw}\right) - \acute{\varepsilon}_w\left(F_{ws}J_s + F_{wf}\tau_f + F_{wf}\acute{\varepsilon}_f F_{fs}J_s\right) \tag{3.29}$$

By moving all other parameters to one side of the equation, J_w will be:

$$J_w = \frac{\tau_w + \acute{\varepsilon}_w\left(F_{ws}J_s + F_{wf}\tau_f + F_{wf}\acute{\varepsilon}_f F_{fs}J_s\right)}{\varepsilon_w + \acute{\varepsilon}_w\left(F_{ws} + F_{wf} - F_{wf}\acute{\varepsilon}_f F_{fw}\right)} \tag{3.30}$$

or:

$$\boxed{J_w = \frac{\tau_w + \acute{\varepsilon}_w\left(F_{ws}J_s + F_{wf}\left(\tau_f + \acute{\varepsilon}_f F_{fs}J_s\right)\right)}{1 + F_{wf}F_{fw}\left(\varepsilon_w + \varepsilon_f - \varepsilon_w\varepsilon_{f-1}\right)}} \tag{3.31}$$

- *Step three: Finding T_w*

By replacing J_f and J_w from (3.24) and (3.31) in equation (3.15), T_w is now the only unknown parameter in this equation and can be easily calculated.

3.4.4. Application of the model

This section shows, through an example, how the analytical model developed in this thesis for predicting the temperature of wall surfaces facing a courtyard can be applied to a typical courtyard. This example can be later used for validating ENVI-met's performance in predicting same parameter.

- *Defining the problem:*

To avoid the complications of calculating multiple view factors, the courtyard selected here, is a cubic courtyard with the dimensions of 6X6X6 m. Emissivity of the floor and the walls are also taken to be identical and equal to 0.85. Walls also have a thermal resistance of 0.5 and a convective coefficient for natural convection of $4\ W/m^2\ °C$. Temperature on the outer surface of the walls (the side facing courtyard) is to be calculated using following known temperatures:

- Temperature on the inner surface of the walls (facing indoors): 21 °C

- Mean air temperature of the courtyard: 18 °C
- Sky temperature: 12 °C
- Floor surface temperature: 18 °C

- *Mathematical Interpretation of the problem:*

- Cubic courtyard $\therefore$ $F_{fs} = F_{ws} = F_{wf} = 0.2$; $F_{fw} = 0.8$
- $\varepsilon_w = \varepsilon_f = 0.85$
- $h_c = 4\ W/m^2\,°C$
- $T_r = 294\,°K$
- $T_a = 291\,°K$
- $T_s = 285\,°K$
- $T_f = 291\,°K$
- $R_w = 0.5\ m^2K/W$
- $T_w = ?$

- *Solution:*

Sky is assumed to be a black body and therefore:

$$J_s = \sigma {T_s}^4 = 5.67 \times 10^{-8} \times 285^4 = 374.08 \qquad \text{(a)}$$

By definition:

$$\acute{\varepsilon}_w = 1 - \varepsilon_w \qquad \text{(b)}$$

$$\acute{\varepsilon}_f = 1 - \varepsilon_f \qquad \text{(c)}$$

and since in the problem $\acute{\varepsilon}_w$ and $\acute{\varepsilon}_f$ are assumed equal, then:

$$\acute{\varepsilon}_f = \acute{\varepsilon}_w = 1 - \varepsilon_w = 1 - 0.85 = 0.15 \qquad \text{(d)}$$

τ_f is also defined as:

$$\tau_f = \sigma {T_f}^4 \varepsilon_f = 5.67 \times 10^{-8} \times 291^4 \times 0.85 = 345.60 \qquad \text{(e)}$$

By putting above values in equation (3.31):

$$J_w = \frac{5.67 \times 10^{-8} \times {T_w}^4 \times 0.85 + 0.15\big(0.2 \times 374.08 + 0.2(345.6 + 0.15 \times 0.2 \times 374.08)\big)}{1 + 0.2 \times 0.8(0.85 + 0.85 - 0.85 \times 0.85 - 1)} = \frac{4.82 \times 10^{-8} {T_w}^4 + 21.93}{1}$$

thus J_w is:

$$J_w = 4.82 \times 10^{-8} {T_w}^4 + 21.93 \qquad \text{(f)}$$

and when put in (3.24):

$$J_f = 345.60 + 0.15\left(0.2 \times 374.08 + 0.8 \times \left(4.82 \times 10^{-8}{T_w}^4 + 21.93\right)\right)$$
$$= 345.60 + 0.15\left(74.82 + 3.86 \times 10^{-8}{T_w}^4 + 17.54\right)$$

So:

$$J_f = 0.58 \times 10^{-8}{T_w}^4 + 359.45 \qquad (g)$$

Equation (3.15) can be now rewritten as:

$$\frac{294 - T_w}{0.5} = 4(T_w - 291) + \left(0.2\left(4.82 \times 10^{-8}{T_w}^4 + 21.93 - 374.08\right) + 0.2\left(4.82 \times 10^{-8}{T_w}^4 + 21.93 - 0.58 \times 10^{-8}{T_w}^4 - 359.45\right)\right)$$

or:

$$588 - 2T_w = 4T_w - 1164 + 0.96 \times 10^{-8}{T_w}^4 - 70.43 + 0.85 \times 10^{-8}{T_w}^4 - 67.5$$

Therefore:

$$1.81 \times 10^{-8}{T_w}^4 + 6T_w = 1889.93 \qquad (h)$$

and as a result:

$$T_w = 292.8°K = 19.8°\text{C}$$

3.4.5. Cross-validation against ENVI-met

To validate the results predicted by the analytical model presented in this chapter against those predicted by ENVI-met, a model must be constructed in ENVI-met that represents all the settings defined for the courtyard in 3.4.4. This means that all characteristics of different surfaces as well as environmental features should be exactly identical to what was introduced in the example above.

- Environmental factors used here (i.e. temperature and convective coefficient of the air and ground temperature) are all part of the normal input data to the programme and can be easily set equal to the ones in the example problem.

Emissivity of the floor surface could also be added directly to the programme and, therefore, complete the setting for one of the three surfaces (floor surface).

- The fictitious black body surface on top of the courtyard (representing sky) cannot be directly added to the model. However, since the only heat exchange happening between the sky surface and other components of the model is through radiation, only defining the emissivity of the sky (ε_s=1) and its view factor from other surfaces will suffice to cover the impact of this surface.
- A major part of the analytical model is concerned with solving the heat balance on the wall surrounding the courtyard and without considering this part, the biggest surface of the model cannot be defined. This needs setting the conditions on both sides of the wall, the side facing outside (the courtyard) and the side facing inside (the room). ENVI-met is an outdoor simulation program and has not been designed to deal with indoor environment and is, therefore, incapable of doing this.

This establishes the need to use an indoor simulation programme in conjunction with ENVI-met to deal with the issue of heat balance on the walls. Next chapter is dedicated to developing a method to facilitate the use of these two simulation tools (ENVI-met for the outdoor environment and TRNSYS for the indoors) in an integrated manner. When, by using this method, the conditions on both sides of the wall are defined and set, the exact conditions of the courtyard, described in 3.4.4 can be simulated and since the settings in both methods (analytical modelling and simulation) are identical, this constitutes a good test for agreement.

For now and without having an established method for using these two programs together, the indoor and outdoor simulations needed here can be performed separately and the results can be linked to make a conclusion.

- *Plan:*

Having the courtyard in a steady state, by definition, means that the amount of heat entering the courtyard should be equal to the amount of heat leaving it. In the absence of solar radiation (night-time), the entering of heat energy happens through the walls and from the rooms if the temperature of the inner surface of the wall is more than the outer surface (in the opposite case, the argument can be reversed). The energy gained this way is transferred either by convection to the air in the courtyard or by radiation to other surrounding surfaces (Figure 3.17). If the air temperature in the courtyard is kept constant, this means that the air in the courtyard is not receiving any of the energy entering the system and all of this energy is lost through radiation. This fact can be a good base for the parallel simulation of the heat entering the courtyard through the walls (by TRNSYS) and the heat lost through radiation to sky and/or floor (by ENVI-met).

Therefore, the plan is to find the surface temperature, at which all the heat entering the courtyard through the walls is lost by radiation to other surfaces. The entering heat can be calculated by TRNSYS, which is capable of solving the energy balance of the wall. The calculation of the radiative heat loss, while the outdoor air temperature is constant, is also a task that ENVI-met can deal with.

- *Step 1) Calculating heat gain by TRNSYS:*

The wall between the courtyard and its surrounding indoor space was simulated in TRNSYS, under a constant temperature of 294°K (after the problem described in 3.4.4) for the inner surface of the wall and a steadily changing temperature of 290 to 295°K for the outer surface of the wall during a 10 hour period (after an 8 hour initialisation stage). Simulations calculated the amount of heat loss from the room through the wall (which is equal to the heat, gained by the courtyard) through these changes. The results for these simulations are presented in Figure 3.18.

The diagram shows a linear relation between the temperature of the outer surface of the wall and the energy lost through it. At 294°K (when the temperatures of the surfaces on two sides of the wall are equal) there is no heat exchange through the

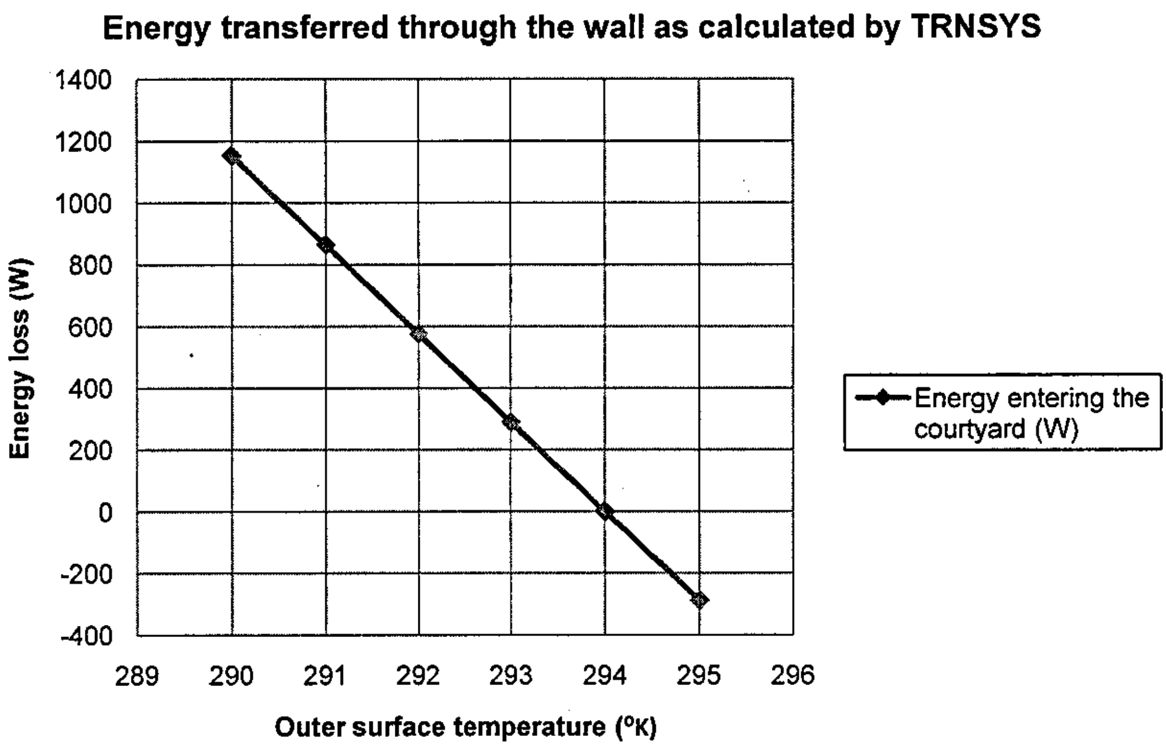


Figure 3.18 the amount of heat entering the courtyard for different outer surface temperatures

wall. As would be expected, for values lower than 294°K (when the courtyard is colder than the room), the heat moves in positive direction (from room towards courtyard) and for higher temperatures (when courtyard is warmer) in the opposite direction.

- *Step 2) Calculating heat loss by ENVI-met:*

To run the simulation, the model of the courtyard and its surrounding building is structured as in Figure (3.19). This figure shows a simple 6x6 m courtyard surrounded by a 6 m high wall with a thickness of 0.5 m (lowest possible dimension for an object in ENVI-met). To minimise the possible effects of the surrounding environment, the whole simulation area was limited to this small setting and the nesting grid (as defined in 3.2) started immediately behind the surrounding wall. A grid by size of 0.5m was formed across the courtyard and the air temperature in all grid cells next to the wall (bold cells in Figure 3.18) was kept constant at T_a ($291\,°K$ in the presented example) and the amount of radiative heat loss from the surface of the wall was calculated for different surface temperatures.

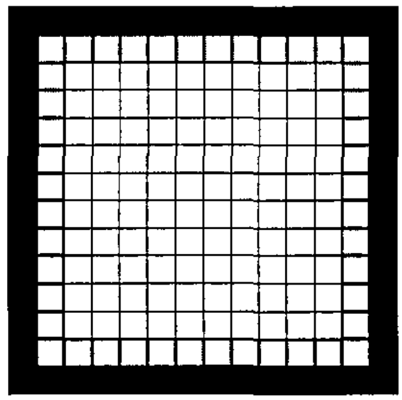


Figure 3.19 The core simulated area

In this simulation, like TRNSYS simulations described above, an initialisation period of 8 hours was observed and then during a 10 hour period, the temperature of the surface of the wall (i.e. the surface, facing courtyard) changed steadily through a 10 hour period from 290°K to 295°K. The total amount of the heat moving out from the courtyard was calculated in each stage and the results were plotted in a diagram that is presented in Figure 3.20.

It is observed from the diagram that when the courtyard walls are cold (T_w<292.2°K), the courtyard is a recipient of energy from the environment and by heating up the wall surfaces of the courtyard, the courtyard reaches a state that starts emitting energy to its surroundings.

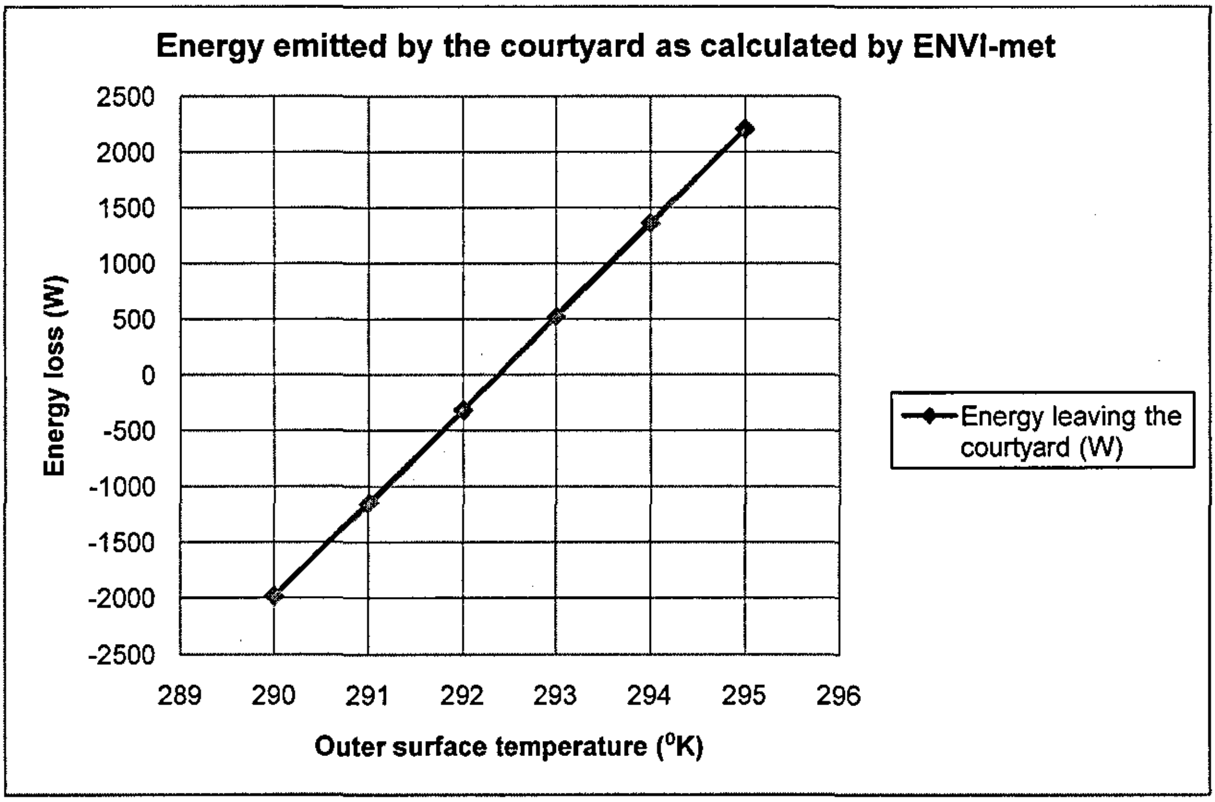


Figure 3.20 The amount of heat leaving the courtyard for different outer surface temperatures

- *Step 3) Cross validation*

Comparing the two diagrams presented in Figures 3.18 and 3.20, shows that at exact surface temperature of 292.8°K (for the outer surface of the walls surrounding the courtyard) the amounts of energy received and produced by courtyard as a system are equal. In other words, when the surface temperatures reach this point, the courtyard is at a steady state. This is in complete agreement with the results produced by the analytical model for this courtyard (3.4.4).

This confirms that although simulating surface temperatures based on the indoor environment of the buildings is outside the abilities of ENVI-met, calculation of the relations between these surface temperatures and other environmental factors in the surroundings by ENVI-met have a satisfactory degree of accuracy.

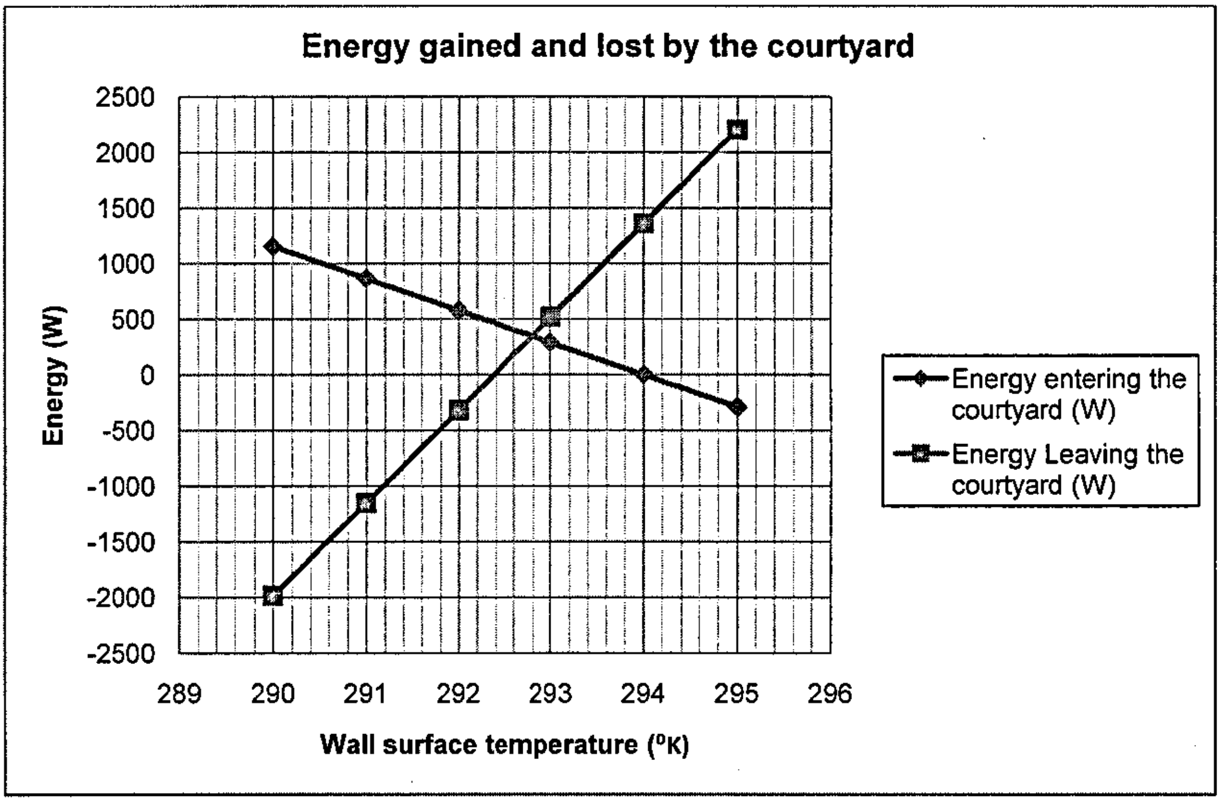


Figure 3. 21 comparing the amount of energy gained and lost by the courtyard for different surface temperatures

3.5 Discussion

In this chapter, candidate outdoor simulation programmes were reviewed and their relevance to the needs of this thesis was investigated. This investigation led to selecting ENVI-met as the simulation tool used in this research for studying environmental conditions outdoors. A brief review of the basics of ENVI-met modelling and simulation was also presented to show the approach taken by the program in modelling and simulation of outdoor environment.

Known concerns about ENVI-met were also discussed and the need for further validation was established. Two different validation approaches were applied and the results achieved by these approaches can be summarised as follows:

- The empirical validation approach showed some inconsistencies between the average air temperatures measured in three courtyards and the average air temperature predicted by ENVI-met;
- This inconsistency were further investigated and its relation with the inaccuracy of the predicted surface temperatures was confirmed;
- The air temperatures calculated for areas of the courtyard far enough from the surrounding walls proved to show good agreement with direct observations;
- The surface temperatures predicted by ENVI-met, particularly during daytime, did not show a satisfactory level of accuracy. However, it was argued that this could be solved by coupling ENVI-met with an indoor simulation program;
- The analytical validation approach proved that when linked with an indoor simulation program, ENVI-met's treatment of the energy emitted and received by surrounding surfaces is acceptably accurate.

As a result of these two sets of validations, ENVI-met can be considered a reliable tool for predicting the environmental conditions outdoors, provided that careful consideration is applied on the surface temperatures of the walls as affected by their indoor environment. Chapter four will discuss these considerations as part of a broader idea of integrating the processes of indoor and outdoor simulation.

4. ■ Integrated simulation of indoor and outdoor environments

ENVI-met simulations that were introduced in Chapter 3, predict the outdoor conditions in the open space. They also provide information needed for simulating the indoor conditions in a building through an appropriate programme. To do this, it is necessary to appropriately connect 'outdoor' and 'indoor' simulation programmes. This is one of the tasks of this research that is discussed in this chapter.

In order to achieve this goal, some of the available simulation packages dealing with the indoor environment are discussed in this chapter and one of them is selected to perform the task required by this research. Afterwards, the process of connecting this programme with ENVI-met, to provide the basis for an integrated method of simulating indoor and outdoor environments, is explained. The chapter will also discuss how this integrated method could be utilised in the process of decision-making at the design stage of a building or an urban development.

4.1. Indoor simulation programmes

Compared to simulation programmes dealing with outdoor conditions, there is a wider range of indoor energy performance simulation tools. Crawley et al (2005) list 25 of these simulation tools that are currently used and promoted. Here, eight of these tools are reviewed based on the extent of their use in academic and/or professional environments, availability to the researcher and relevance to the current study. A short introduction on these eight programmes (as introduced by Crawley et al 2005) is presented in following paragraphs. From the review, the most appropriate tool for this research is selected and introduced.

4.1.1. BSim Version 4.4.12.11

(www.bsim.dk)

BSim provides user-friendly simulation of detailed, combined hygrothermal simulations of buildings and constructions. The package comprise several modules: SimView (graphic editor), tsbi5 (building simulation), SimLight (daylight), XSun (direct sunlight and shadowing), SimPV (photovoltaic power), NatVent (natural ventilation) and SimDxf (import from CAD). BSim has been used extensively over the past 20 years, previously under the name tsbi3. Today BSim is the most commonly used tool in Denmark, and with increasing interest in other countries, for energy design of buildings and for moisture analysis.

4.1.2. EnergyPlus Version 1.2.2, April 2005

(www.energyplus.gov)

EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. It is a simulation engine with input and output of text files. Loads calculated (by a heat balance engine) at a user-specified time step (15 minute default) are passed to the building systems simulation module at the same time step. The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution provides more accurate space temperature prediction, crucial for system and plant sizing and occupant comfort calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and inter-zone air flow.

4.1.3. ESP-r Version 10.1, February 2005

(www.esru.strath.ac.uk/Programs/ESP-r.htm)

ESP is a general purpose, multi-domain (building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow) simulation environment which has been under development for more than 25 years. It follows the pattern of `simulation follows description` where additional technical domain solvers are invoked as the building and system description evolves. Users control the complexity of the geometric, environmental control and operations to match the requirements of particular projects. It supports an explicit energy balance in each zone and at each surface. ESP-r is distributed under a GPL license. The web site also includes an extensive publications list, example models, source code, tutorials and resources for developers.

4.1.4. IDA ICE Version 3.0, build 15, April 2005

(www.equa.se/ice)

IDA Indoor Climate and Energy (IDA ICE) is based on a general simulation platform for modular systems, IDA Simulation Environment. Physical systems from several domains are in IDA described using symbolic equations, stated in either or both of the simulation languages Neutral Model Format (NMF) or Modelica. IDA ICE offers separated but integrated user interfaces to different user categories:

• Wizard interfaces lead the user through the steps of building a model for a specific type of study. The Internet browser based IDA Room wizard calculates cooling and heating load.

• Standard interface for users to formulate a simulation model using domain specific concepts and objects, such as zones, radiators and windows.

• Advanced level interface – where the user is able to browse and edit the mathematical model of the system.

• NMF and/or Modelica programming – for developers.

4.1.5. IES <VE> Version 5.2, December 2004

(www.iesve.com)

The IES <Virtual Environment> (IES <VE>) is an integrated suite of applications linked by a common user interface and a single integrated data model. <Virtual Environment> modules include:

• ModelIT – geometry creation and editing
• ApacheCalc – loads analysis
• ApacheSim – thermal
• MacroFlo – natural ventilation
• Apache HVAC – component based HVAC
• SunCast – shading visualisation and analysis
• MicroFlo – 3D computational fluid dynamics
• FlucsPro/Radiance – lighting design
• DEFT – model optimisation
• LifeCycle – life-cycle energy and cost analysis
• Simulex – building evacuation

The program provides an environment for the detailed evaluation of building and system designs, allowing them to be optimized with regard to comfort criteria and energy use.

4.1.6. PowerDomus Version 1.5, September 2005

(www.pucpr.br/lst)

PowerDomus is a whole-building simulation tool for analysis of both thermal comfort and energy use. It has been developed to model coupled heat and moisture transfer in buildings when subjected to any kind of climate conditions, i.e., considering both vapor diffusion and capillary migration. Its models predict temperature and moisture content profiles within multi-layer walls for any time step and temperature and relative humidity for each zone.

PowerDomus allows users to visualize the sun path and inter-buildings shading effects and provides reports with graphical results of zone temperature and relative humidity, PMV and PPD, thermal loads statistics, temperature and moisture content within user-selectable walls/roofs, surface vapor fluxes and daily-integrated moisture sorption/ desorption capacity.

4.1.7. Tas Version 9.0.7, May 2005

(www.edsl.net)

Tas is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems. The main module is Tas Building Designer, which performs dynamic building simulation with integrated natural and forced airflow. It has a 3D graphics based geometry input that includes a CAD link. Tas Systems is a HVAC systems/controls simulator, which may be directly coupled with the building simulator. It performs automatic airflow and plant sizing and total energy demand. The third module, Tas Ambiens, is a robust and simple to use 2D CFD package which produces a cross section of micro climate variation in a space. Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations which include advanced control functions on aperture opening and the ability to simulate complex mixed mode systems. The software has heating and cooling plant sizing procedures, which include optimum start. Tas has 20 years of commercial use in the UK and around the world.

4.1.8. TRNSYS Version 16.0.37, February 2005

(www.sel.me.wisc.edu/trnsys)

TRNSYS is a transient system simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components. TRNSYS components (referred to as "Types") may be as simple as a pump or pipe, or as complicated as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, and building input data is entered through a dedicated visual interface (TRNBuild). The simulation engine then solves the system of algebraic and differential equations that represent the whole system. In building simulations, all HVAC-system components are solved simultaneously with the building envelope thermal balance and the air network at each time step. In addition to a detailed multizone building model, the TRNSYS library includes components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc.

The modular nature of TRNSYS facilitates the addition of new mathematical models to the program. In addition to the ability to develop new components in any programming language, the program allows user to directly embed components implemented using other software (e.g. Matlab/Simulink, Excel/VBA, and EES). TRNSYS can also generate executables that allow non-expert to run parametric studies.

4.2. Programme selection

To choose one of these tools for the purpose of this research, the first step is to define a set of criteria that narrows down the choices. These criteria, and the ability of the programmes to meet them, are summarized in Table 4.1.

As this table shows, all seven programmes show good quality in the area of simulation solutions they use i.e. they are all capable of simulating different components of the building and their interactions at the same time and they all have

Table 4.1 Contrasting the capabilities of building energy performance simulation programs

Features	Tas	BSim	EnergyPlus	IDA ICE	IES <VE>	PowerDomus	ESP-r	TRNSYS
Simulation solution								
▪ Simultaneous loads, system and plant solution	x	x	x	x	x	x	x	x
▪ Space temperature based on loads-systems feedback	x	x	x	x	x	x	x	x
▪ Floating room temperatures	x	x	x	x	x	x	x	x
Time step approach								
▪ User-selected for zone/environment interaction		x	x	x	x	x	x	x
▪ User-selected for both building and systems				x	x	x	x	x
Full Geometric Description								
▪ Walls, roofs, floors	x	x	x	x	x	x	x	x
Number of surfaces, zones, systems and equipment unlimited	x	x	x	x	x	x	x	x
Generate hourly data from monthly averages					x			x
Estimate diffuse radiation from global radiation	x		x		x			x
Weather data processing and editing	x					x	x	x

a solution for calculating room temperatures without using any type of environmental control that, as shown later in this chapter, is one of the defining factors of this research. All programmes are also capable of dealing with different geometric characteristics for an indefinite number of interacting surfaces, which due to the complexity of some of the simulations in this study, will become very important.

Tas, BSim and EnergyPlus, due to their limitations in adapting themselves to the time steps chosen by the user, for observing either the building or its electrical and mechanical systems, cannot be the best choices for this study. For Tas this limitation also extends to the user's ability in selecting the frequency of time steps in the interaction of indoor and outdoor environments, which is one of the basic ideas of this research and could not be compromised.

One of the other requirements of the study is the need for hourly data for the whole duration of the simulations and very often this information is not readily available. There are methods to generate these hourly data from daily or even monthly averages with acceptable approximate answers. Among the four remaining programmes only IES <VE> and TRNSYS offer ways to do this task. This narrows down our selection process to only two choices.

The reason that makes TRNSYS a better choice in comparison to the other candidate, is the option provided by this programme for processing and editing all or some of the weather data for trying different scenarios. This can be done by either direct editing of the weather file or adding a new component (or Type in TRNSYS terminology), separate from the weather file, to make necessary amendments on the data affecting the building. When transferring data between ENVI-met and TRNSYS (an example of which was presented in 3.4), this potential proves very helpful.

4.3. TRNSYS components

The creators of TRNSYS describe it as "a modular simulation program that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components" (trnsys.com 2006). These components are called "types" in TRNSYS terminology and may be as simple as a pipe, or as complicated as a multi-zone building model. The components are configured and assembled using a visual interface known as the TRNSYS Simulation Studio, and building input data is entered through another visual interface (TRNBuild). The simulation engine then solves the system of algebraic and differential equations that represent the whole system (trnsys.com 2006).

In addition to a detailed multi-zone building model, the TRNSYS library includes components for "solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells and hydrogen systems", etc (trnsys.com2006). In this section some of the Types used in this thesis are briefly introduced (after Solar Energy Laboratory 2006) and will be referred to only with their type numbers from now on.

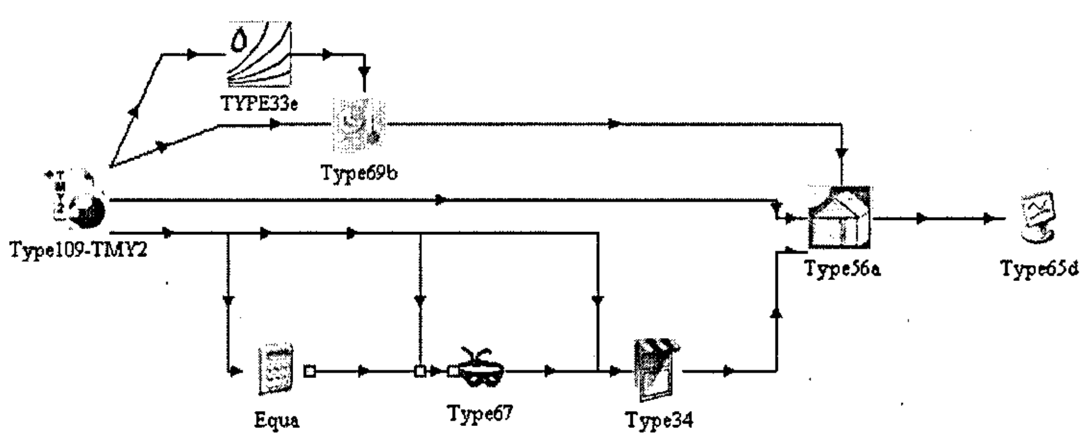


Figure 4.1 TRNSYS types used in this thesis

The order, in which these types are finally used, is demonstrated in Figure 4. At this stage, this figure is just to introduce the way different types are connected in TRNSYS. The reasoning behind the formation of this model is gradually explained in this chapter.

4.3.1. Type 56a

This component models the thermal behaviour of a building having up to 25 thermal zones. The building description is read by this component from a set of external files having the extensions *.bui, *.bld, and *.trn. The files can be generated based on user supplied information by running the processor program called TRNBuild. This Type generates its own set of monthly and hourly summary output files. Using this component allows distinction between different parts of building interiors in regards to their adjacent indoor and outdoor spaces.

4.3.2. Type 34

This component computes the solar radiation on a vertical receiver shaded by an overhang and/or wingwall. A shaded receiver may include left and/or right hand wing walls that extend above and/or below the receiver. The receiver may also include an overhang that can be placed at the top or above the receiver. The overhang may extend to the right and left of the receiver. In Chapter 5 of this thesis, Type 34 is used to define the shadings over the windows of the simulated buildings.

4.3.3. Type 65d

The online graphics component is used to display selected system variables while the simulation is progressing. This component provides variable information and allows users to immediately see if the system is not performing as desired. The selected variables will be displayed in a separate plot window on the screen. In the simulations carried out for the current study, this type was used only as a means of controlling the process and the output data is not displayed via this component. As a common language between TRNSYS and ENVI-met, Microsoft Excel was used for transferring data between the two.

4.3.4. Type 67

Type 67 reads a file containing the angular heights of obstructions that shade a series of openings. For each opening, a numerical ID in ascending order is provided on the first line of the data file. The second line contains the slope of each opening. The third line contains the azimuth of each opening. The fourth line contains a series of absolute surface angles; angles for which obstruction heights will later be provided. The fifth and subsequent lines of the data file each contain the angular height of an arbitrary obstruction as seen from the centre of an aperture while looking in the direction of one of the above provided surface azimuth angles.

Type 67 takes two inputs that give the angle of the sun, two inputs that give total and diffuse radiation on the horizontal and then two inputs for each opening that give the beam and diffuse radiation on each opening. The component returns eleven outputs for each opening in the file. The first output is the fraction of beam radiation that is visible from the opening. The second is the shaded beam radiation on the opening. The third output is the fraction of diffuse radiation incident on the surface. The fourth and fifth outputs give the shaded diffuse and shaded total radiation respectively (both on the plane of the opening). Output six through eleven (for each opening) give the same values in the plane of the horizontal.

This type is of very high importance when comparing different configurations of buildings around an open space (such as a courtyard). The shading caused on surfaces and openings by external objects can be considered as one of the main differences between different design layouts and this component can deal with this element in the investigations.

4.3.5. Type 69b

This component determines an effective sky temperature, which is used to calculate the long-wave radiation exchange between an arbitrary external surface and the atmosphere. The effective sky temperature is always lower than the current ambient temperature. The black sky on a clear night for example, is assigned a low effective sky temperature to account for the additional radiative losses from a surface exposed to the sky. In this Type, the cloudiness of the sky can also be calculated based on user provided dry bulb and dew point temperatures.

4.3.6. Type 33e

This component takes as input the dry bulb temperature and relative humidity of moist air and calls the TRNSYS Psychrometrics routine, returning the following corresponding moist air properties: dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, absolute humidity ratio and enthalpy.

This Type is used as one of the main tools to link TRNSYS to ENVI-met in this chapter. It enables user to override the input air temperature and relative humidity calculated in TRNSYS by those given by ENVI-met at any point and will be frequently used in this chapter.

4.3.7. Type 109-TMY2

This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and processing the solar radiation data to obtain tilted surface radiation and angle of incidence for an arbitrary number of surfaces. The weather data file used in this program can be either the real weather data to simulate the general environment surrounding a building, or the data that are given as an output of previous simulations by ENVI-met. In this chapter, this component is used, inter alia, for transferring surface radiation values from ENVI-met to TRNSYS.

4.4. Integrating indoor and outdoor simulations

It was discussed in full detail in Chapter 3 that for achieving reliable results for the thermal interactions on and around the walls separating an indoor environment and a small enclosed outdoor environment (like a courtyard), there has to be a simulation programme able of simultaneous consideration of the interactions on both sides of this wall. In the same chapter, the process of dual application of ENVI-met and TRNSYS for achieving accurate results for surface temperatures of the wall surrounding the courtyard was demonstrated and the importance of an integrated use of these two programmes in similar investigations was expressed.

In this section, the two aforementioned simulation programmes, TRNSYS for indoor simulations and ENVI-met for "outdoor" simulations are linked in order to assess the energy performance of a small scale house as influenced by its adjacent outdoor space conditions (e.g. the courtyard). The Following pages report on the challenges encountered in establishing the interaction between the two programmes, together with approaches that have been used to solve some of the problems. The objective is to establish a method that enables a designer to evaluate and compare heating and cooling energy demands for a range of house designs, in singular and multiple urban configurations, as well as the thermal conditions of the adjacent outdoor space (yard or courtyard) and their effect on outdoor thermal comfort. For this reason, air temperature is taken as the main defining factor and the major metric of the energy performance in the building as well as its state of thermal comfort. This is because the air temperature is the variable being treated in the simulation process. All other environmental factors such as humidity, air speed, etc. can be given as given constant values for all configurations examined, and, therefore, have an equal impact on all types in situations tested. This work will provide the basis for the development of a simulation tool that addresses the thermal interaction between indoor and adjacent outdoor spaces in an integrated manner.

4.4.1. Setting

To achieve this, a hypothetical courtyard house is created and used as an exemplar case to demonstrate the procedure. This is the same courtyard house model used in 3.4.4 and 3.5.5 for cross-validation of ENVI-met and the analytical model for predicting nocturnal surface temperatures in a courtyard presented in Chapter 3. Simulations will be run for this house under sample yearly weather data to assess the climatic impacts on the building. The step-by-step procedure to do this is explained in the following pages. The information sought by this procedure are metrics for both energy consumption inside the building and thermal comfort outside in the courtyard, in a way that allows comparison between similar buildings.

The main parameters discussed in this section are as follows:

- T_o: Outdoor air temperature. This is the temperature of the air wrapping the building from outside, for example, the air temperature as measured on the rooftop.

- T_y: Air temperature in the courtyard. This was demonstrated to be different from T_o (e.g. Figure 3.8).

- T_i: Air temperature in the room adjacent to the courtyard.

- T_s: surface temperature on the outer surface of the wall surrounding the courtyard (the surface facing the courtyard)

4.4.2. Procedure

The procedure of connecting the two programs is discussed here in 8 steps. Each step introduces the input and output data to the procedure and the tool responsible for performing the simulation for that step. The function of each step is also illustrated via a schematic presentation and further explained by the application of that function to a simple courtyard building. The first three steps presented here cover the concept of correcting diurnal surface temperatures as was described in full detail in Chapter 3. Steps 4 to 8 advance the method into predicting heating and cooling loads of the building and thermal comfort environment of the courtyard.

- Step 1:

- Program used: ENVI-met
- Input data: T_o and the sun's position from the weather file
- Output data: T_s and T_y
- Description: By running a basic ENVI-met simulation under defined weather data (either called by ENVI-met from a *.txt file or input manually in the program's input file with the extension *.var), a range of air temperatures for each 3D cell in the grid of the courtyard and surface temperatures for each 2D cell in the grid of the surface of each wall at desired time intervals are

predicted and an average temperature for the selected cells is calculated. This output data is saved in the output file (with *.edi extension). The data in this file is exported to an MS Excel workbook (with the extension *.xls).

- Depiction:

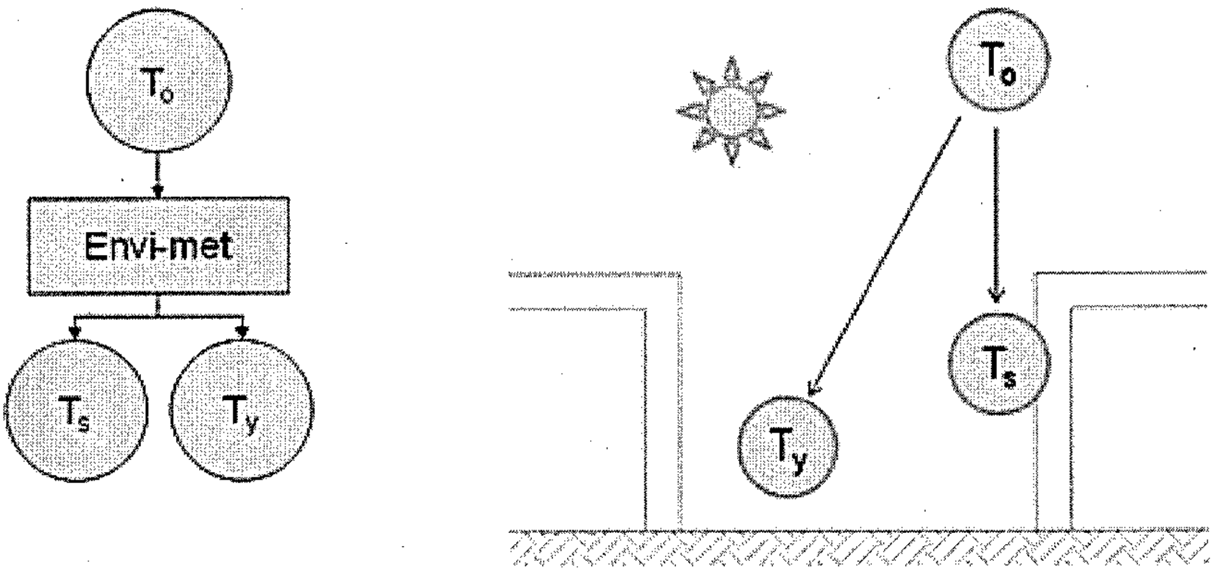


Figure 4.2 Schematic presentation of step 1

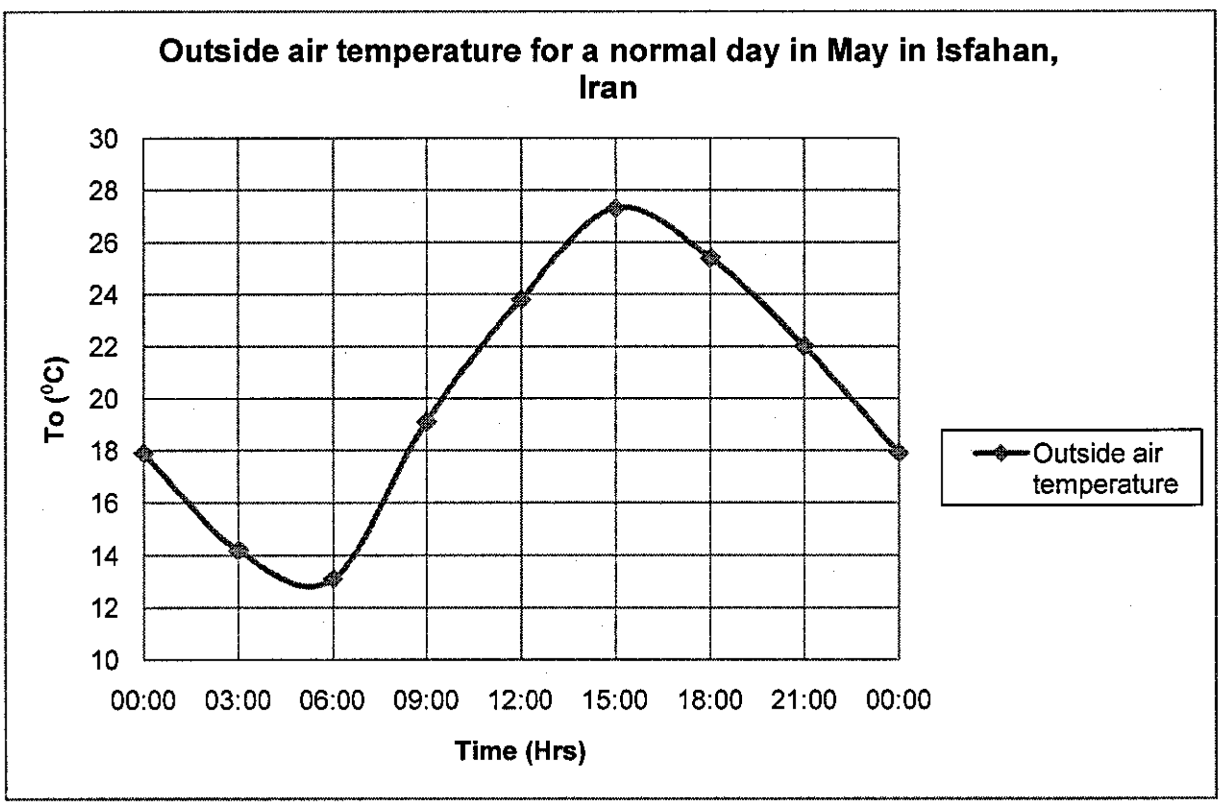


Figure 4.3 T_o from the weather data

Application: ENVI-met simulations were performed for a courtyard (as described in 3.4.5 and illustrated in Figure 3.19) under the weather data from a normal day in May in the city of Isfahan, Iran (figure 4.3). As an output of these simulations, a set of air temperature values for all the grid cells in the environment of the courtyard (average values plotted in Figure 4.4) and a set of surface temperatures for all the grid cells of the outer surface of the walls (average values for the wall facing south demonstrated in Figure 4.5) are produced.

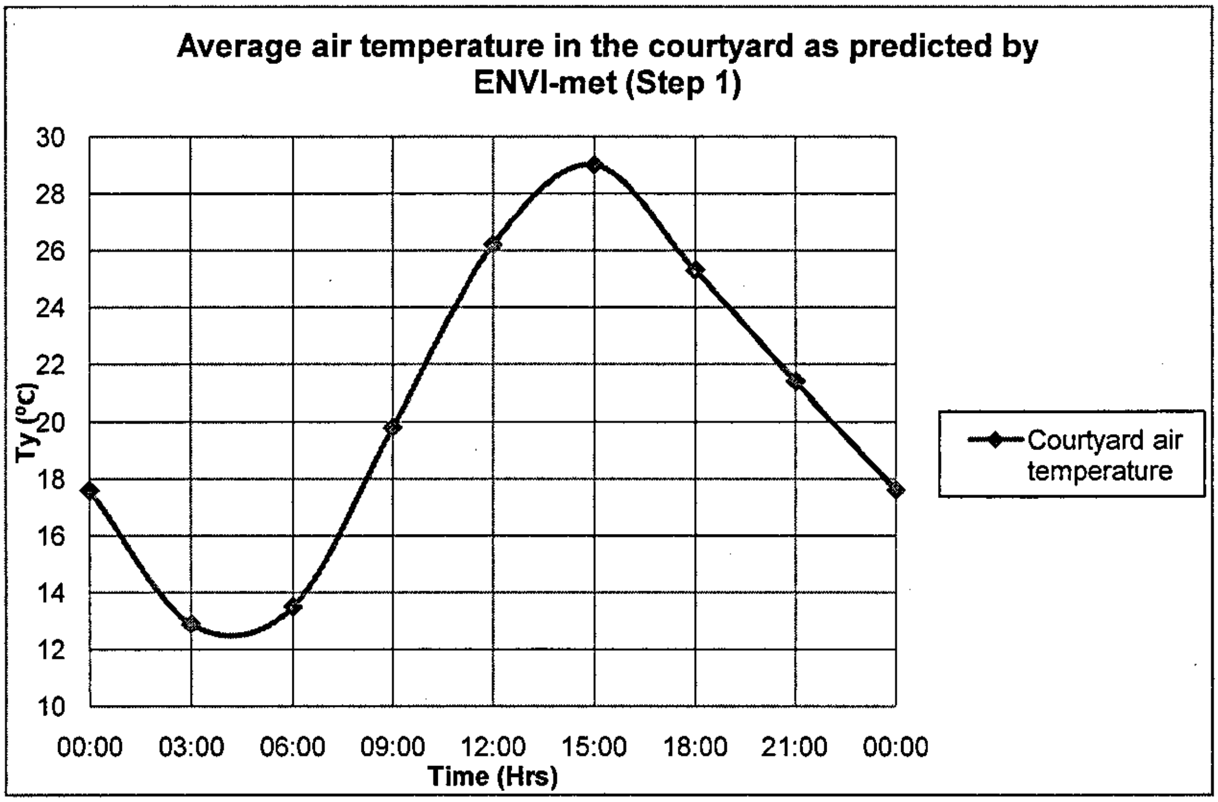


Figure 4.4 T_y as predicted by ENVI-met (Step 1)

- Discussion: As elaborated in Chapter 3 (3.3 and 3.4), these values should not be taken as the final results for either air temperature in the courtyard or surface temperatures of the surrounding walls. These values need to be entered to TRNSYS heat balance calculations on the walls surrounding the courtyard in order to reflect the effect of heat storage in the wall.

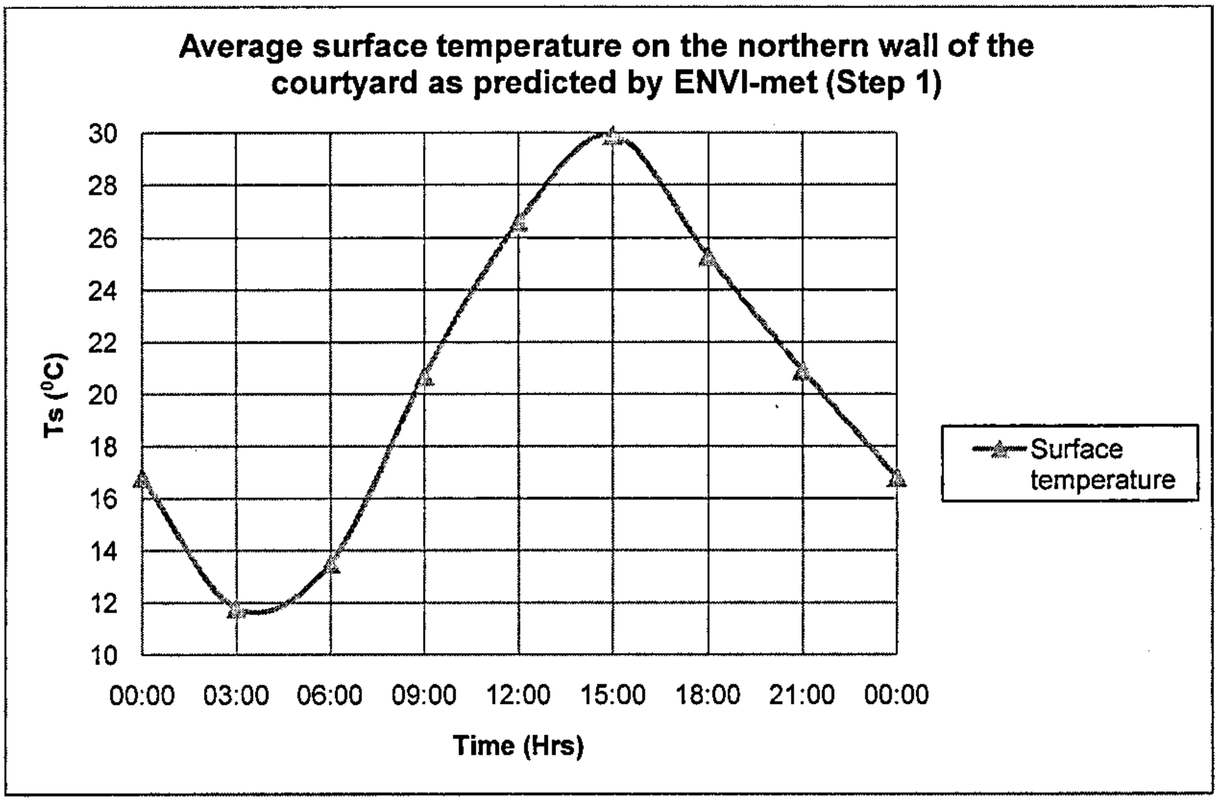


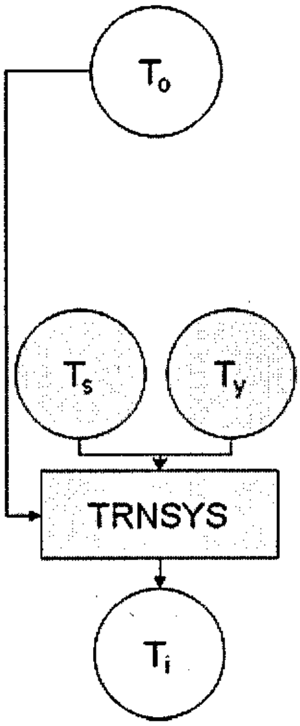
Figure 4.5 Ts as predicted by ENVI-met (Step 1)

- Step 2:

- Program used: TRNSYS
- Input data: T_y and T_s from Step 1, the sun's position and T_o from the weather file
- Output data: T_i
- Description: The building is simulated by TRNSYS, using the usual weather data and the solar irradiation on all sides apart from the side facing the courtyard. The heat gains from solar irradiation on walls surrounding the courtyard is replaced by a wall, the surfaces of which are kept in temperatures equal to the T_s temperatures calculated by ENVI-met in Step 1. A separate set of outside air temperatures (corresponding to T_y values from Step 1) are also added in Type109-TMY2 to apply on these walls. Results for air temperatures

inside the rooms surrounding the courtyard (T_i) are collected from Type 65d in the form of *.xls files.

- Depiction:



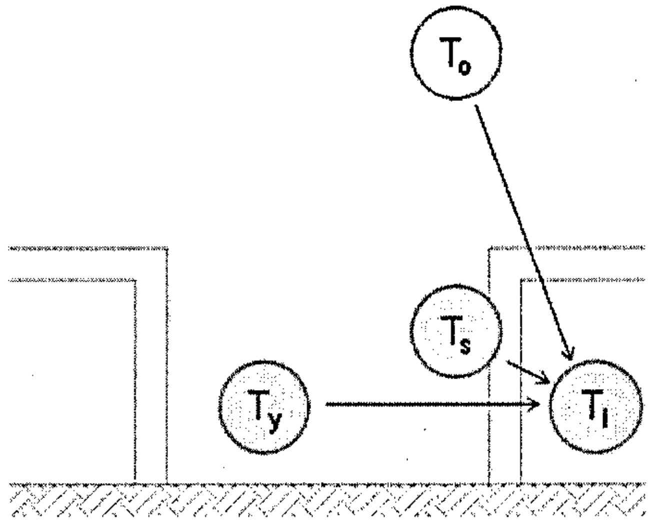


Figure 4.6 Schematic presentation of step 2

- Application: TRNSYS simulations (with the conditions explained above) were performed for a central courtyard building with the same specifications as the one simulated in ENVI-met in Step 1. As an output of these simulations, a set of air temperature values for all the grid cells in the environment of the indoor spaces of the building surrounding the courtyard (average values plotted in Figure 4.7) are produced.
- Discussion: The air temperature inside the room, given by this step in the simulation, is determined as an effect of the fabricated surface temperatures imposed on the outer surface of the courtyard wall. After finding the values for T_i, a second TRNSYS simulation, this time with free running surface

temperatures, is needed to determine more accurate values for T_s. This will be covered in step 3.

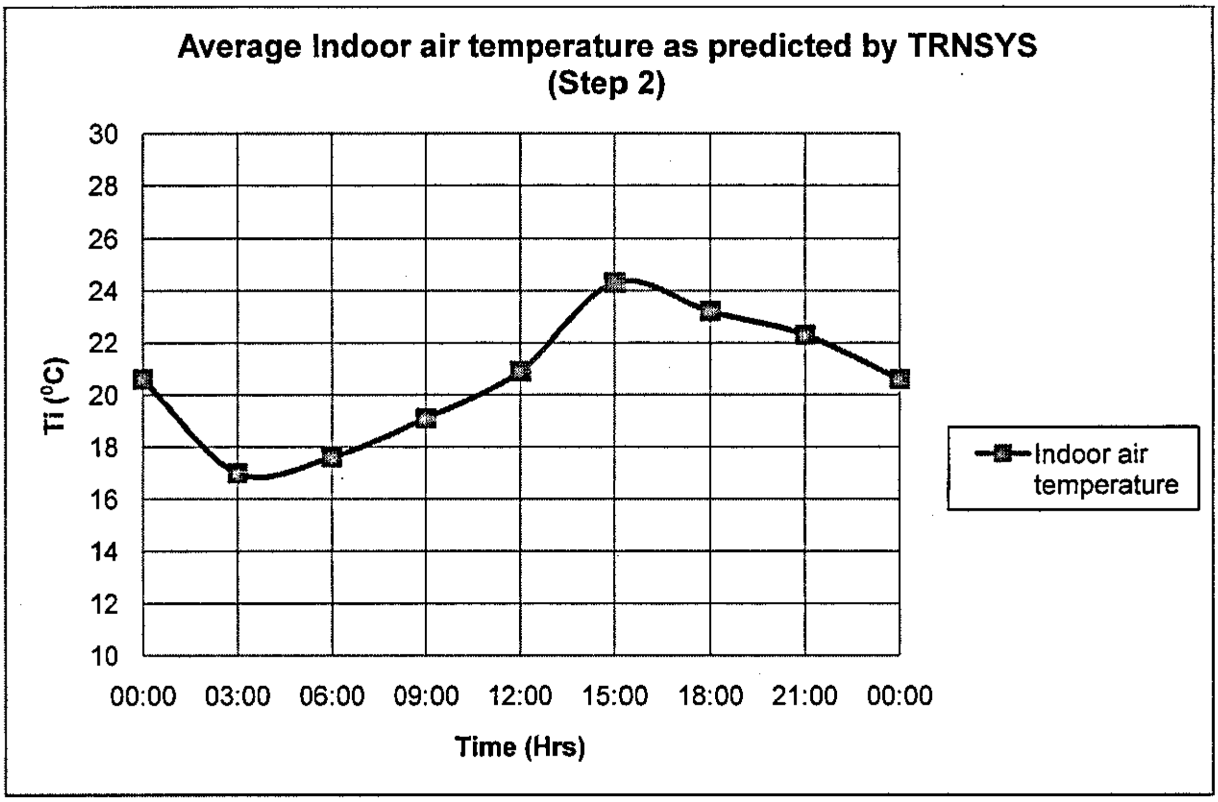


Figure 4.7 T_i as predicted by TRNSYS (Step 2)

- Step 3:

- Program used: TRNSYS
- Input data: T_o from the weather file, T_y from Step 1 and T_i from Step 2
- Output data: T_s
- Description: A second run of TRNSYS simulation is performed to correct the surface temperatures of the walls facing the courtyard predicted by ENVI-met in Step 1. In this run, the outdoor air temperatures (T_i) are considered given (from Step 2) and a new set of surface temperatures (T_s) are calculated in Type 56a. T_y is also treated as known and the values calculated in Step 1 are entered in Type109-TMY2 in a process similar to what was described in Step

2. The results of the simulation of T_s, reported by Type 65d, are exported to an Excel workbook.

- Depiction:

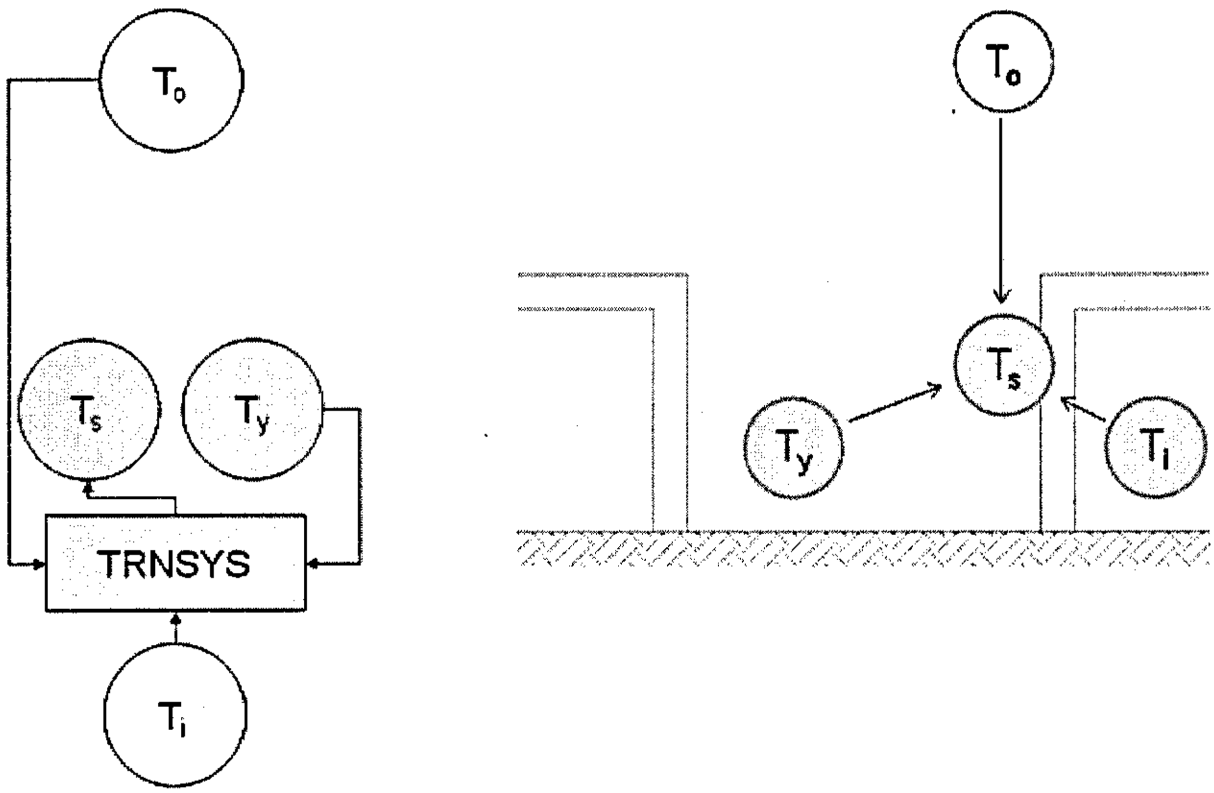


Figure 4.8 Schematic presentation of step 3

- Application: The temperature grid of the outer surface of the walls surrounding the simulated courtyard (calculated previously in Step 1) is corrected in this phase, using the consideration of the indoor environment. An average example of these results is demonstrated in Figure 4.9.

- Discussion: As mentioned in Chapter 3, in this phase of the simulation process, the values for T_s calculated by ENVI-met were replaced by more accurate predictions by TRNSYS. It is a plausible argument that this new set of surface temperatures will, in reverse, affect the air temperature in the courtyard (T_y). This effect will be discussed in the Step 4.

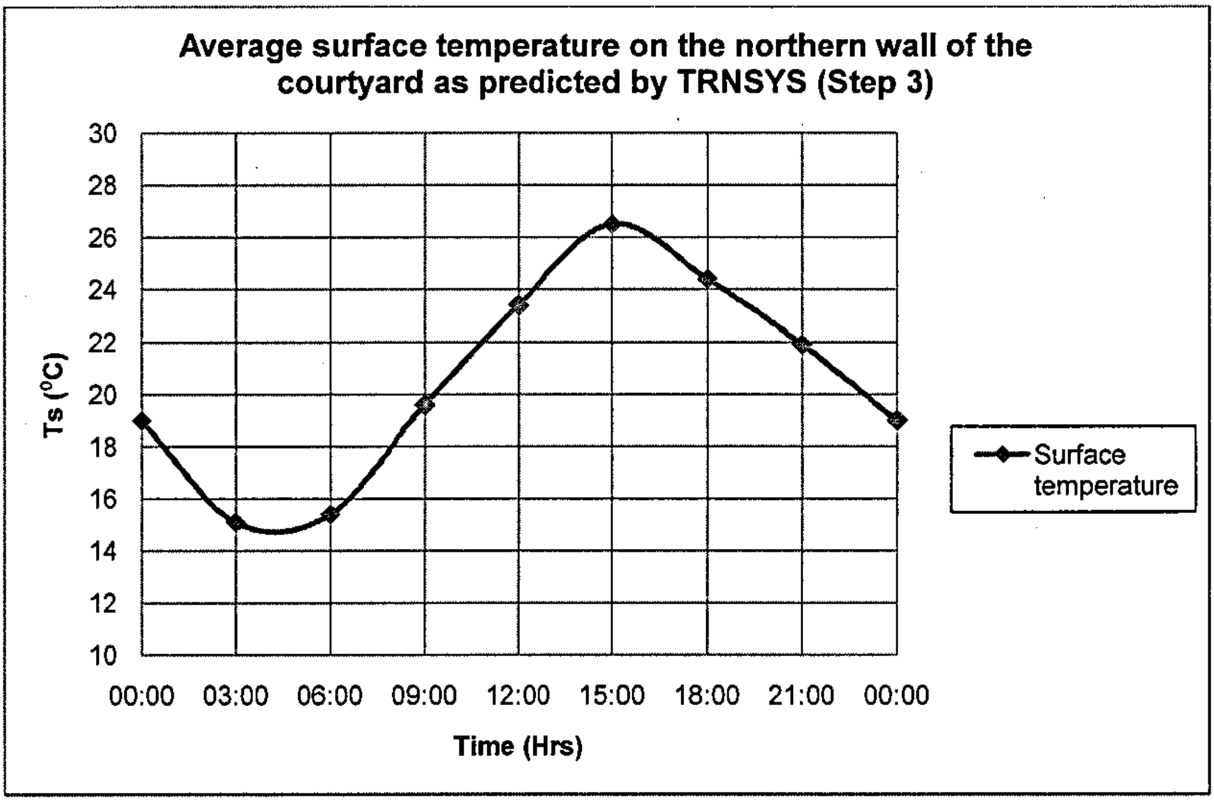


Figure 4.9 T_s as predicted by TRNSYS (Step 3)

- Step 4:

- Program used: ENVI-met and TRNSYS
- Input data: T_s from Step 3 and T_o from the weather file and internal iterations
- Output data: T_y and T_s
- Description: To calculate the air temperatures across the courtyard grid (T_y), the new set of surface temperatures (T_s) from Step 3 are run in ENVI-met for a second time. This will result in a new set of values for T_y that will, in return, lead to the conclusion of the need for a new calculation for surface temperatures (T_s) via TRNSYS. The effects of these two parameters on each other should be simulated for an adequate number of times, until the results are deemed accurate.

- Depiction:

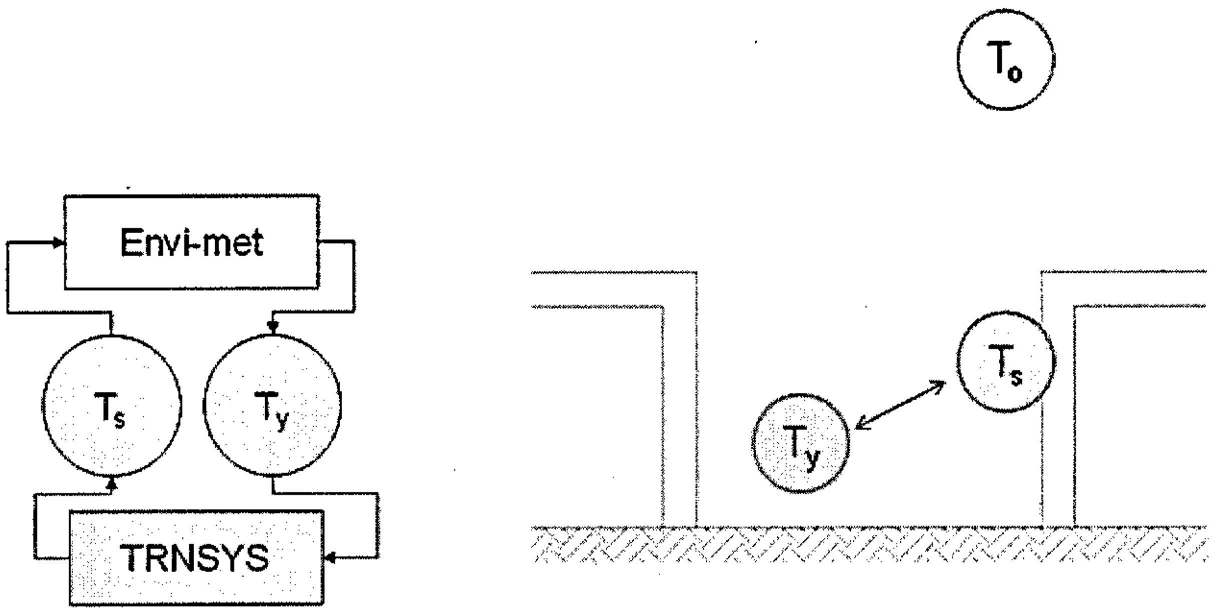


Figure 4.10 Schematic presentation of step 4

Application: The results for T_s from Step 3 (e.g. Figure 4.9) will be used as an input into ENVI-met to generate new values for T_y. Similarly, to account for the effect of the new T_y on surface temperatures, a new TRNSYS simulation can be performed. The results of this simulation (T_s values) are again fed back to ENVI-met to address the changes in T_y values. These iterations must go on until the difference between two consecutive sets of results (for both T_y and T_s) for all grid cells is restricted in an acceptable range. For the typical building simulated here, a maximum of 0.5 °C difference between two consecutive sets of results is taken as reasonable. The average values for courtyard air temperatures and surface temperatures on the northern wall of the courtyard are presented in Figures 4.11 and 4.12.

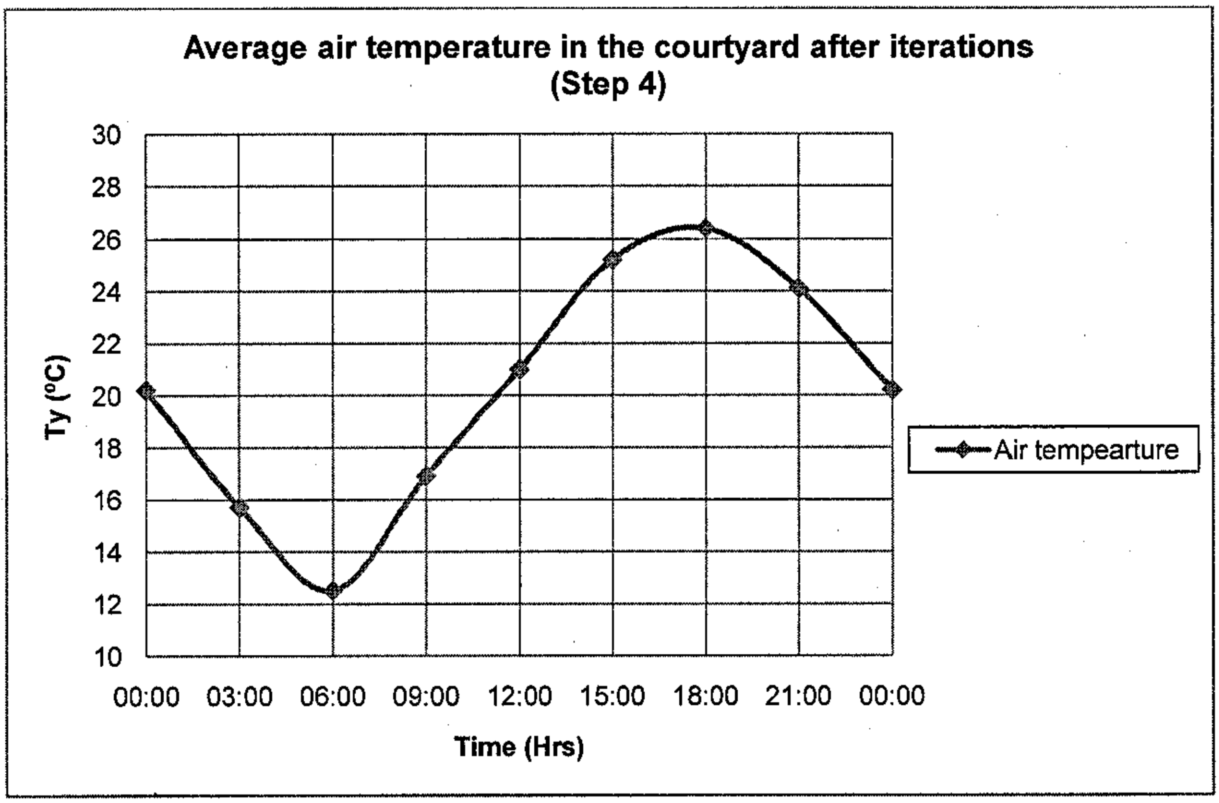


Figure 4.11 T_y after iterations

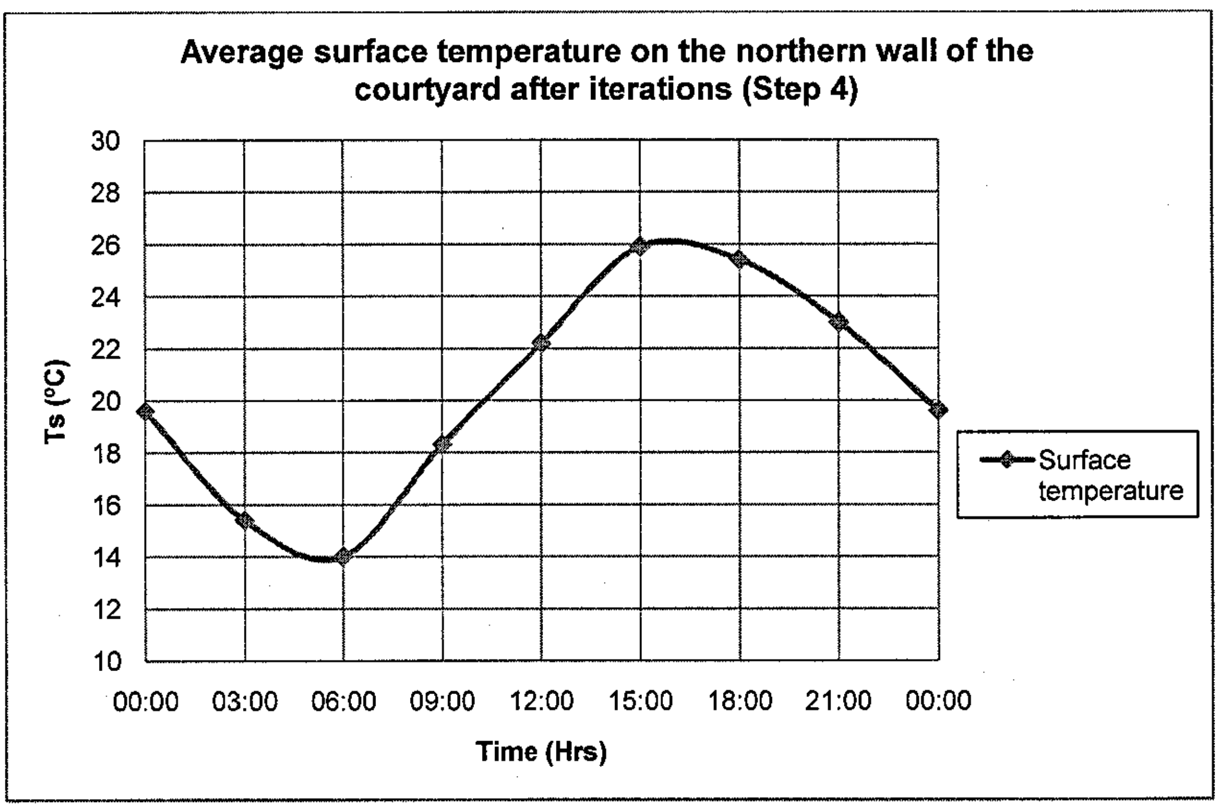


Figure 4.12 T_s after iterations

- Discussion: By calculating final corrected values for the temperature of the air and the surfaces around the building, all the required data are defined for running a final round of simulations in TRNSYS, in order to determine the finalised set of values for air temperatures inside the building (T_i).

- Step 5:

- Program used: TRNSYS
- Input data: T_o from the weather file, T_y and T_s from Step 4
- Output data: T_i
- Description: By defining a proxy Type 109-TMY2 component for courtyard surfaces and replacing the outdoor temperatures (T_o) with courtyard air temperatures (T_y) from Step 4 and fixing the surface temperatures of these walls (in Type 56a) on the values resulted from Step 4, values for indoor air temperature of the building (T_i) can be finalised.
- Depiction:

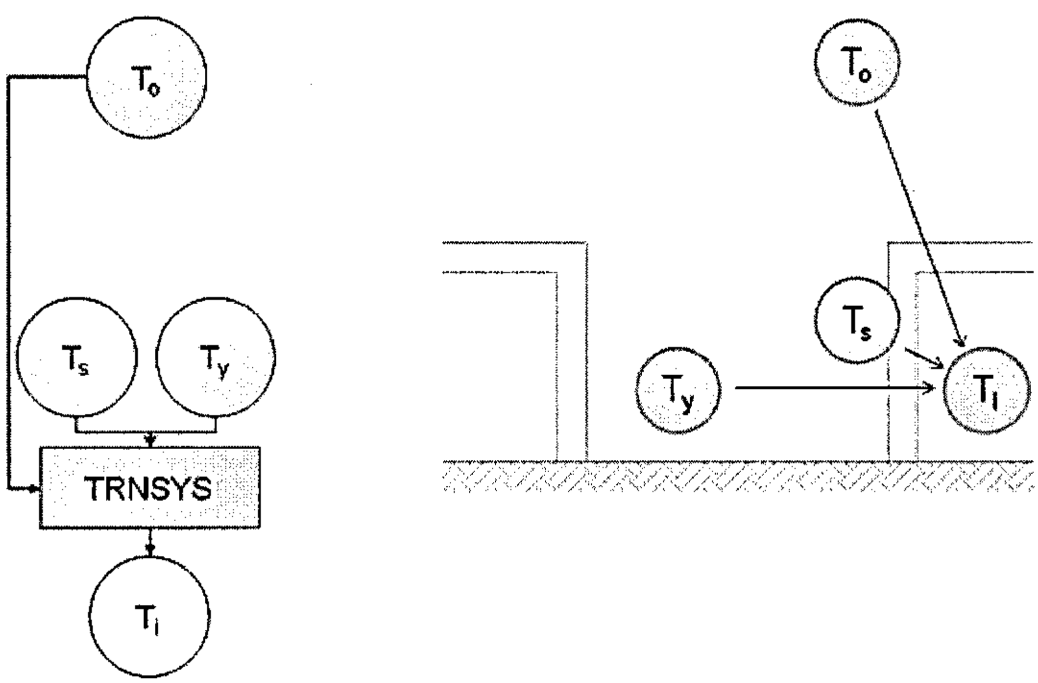


Figure 4.13 Schematic presentation of step 5

- Application: grids for the outer surface temperatures of the walls surrounding the simulated courtyard and the air temperatures inside the courtyard (calculated previously in Step 4) are used in this phase, in order to generate the final set of values for indoor air temperature in the building simulated. An average example of these results is demonstrated in Figure 4.14.
- Discussion: T_i calculated in this step is a prediction of the actual air temperatures that can be measured inside the building. These values can contribute to the assessment of the thermal sensation and consecutively, the amount of heating or cooling needed to maintain this sensation within an acceptable range inside the building. These heating and cooling loads are calculated in the next step.

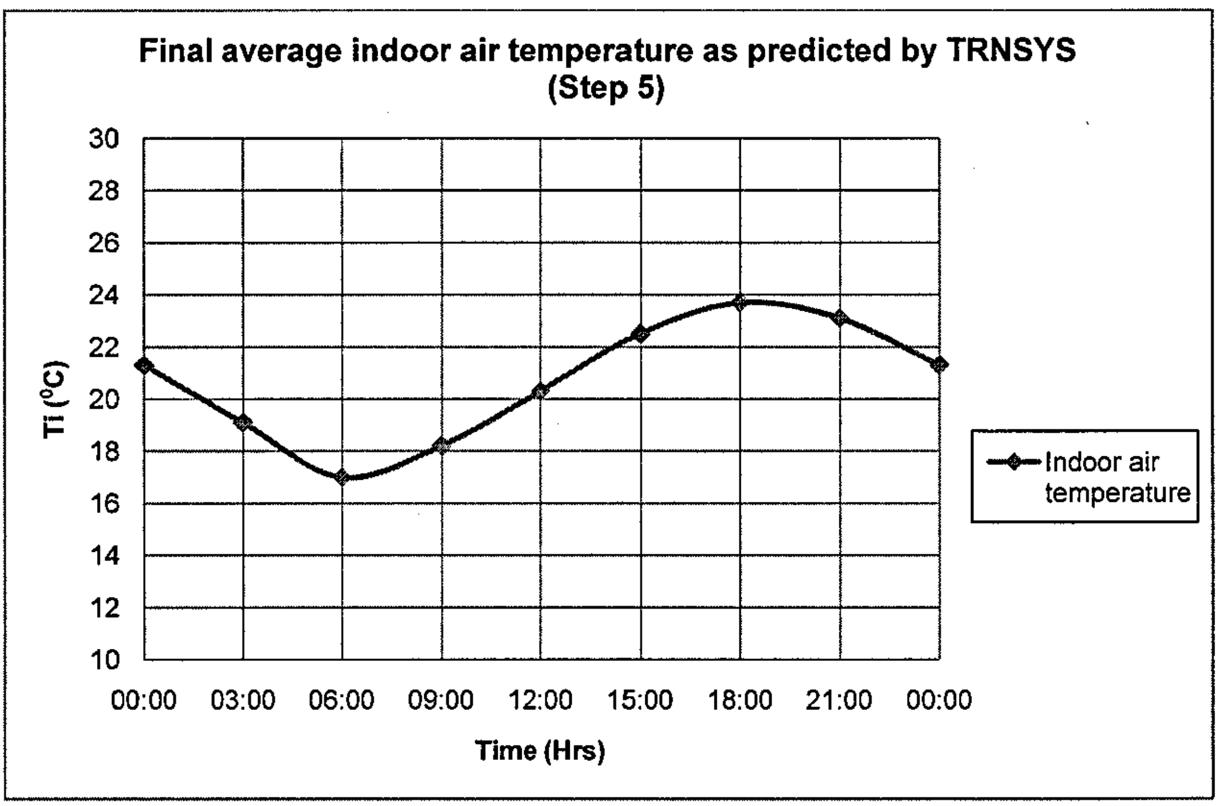


Figure 4.14 Final T_i as predicted by TRNSYS

- **Step 6:**

- Program used: TRNSYS
- Input data: T_i from Step 5 and set temperatures from local regulations
- Output data: Set T_i and heating and cooling loads
- Description: In order to keep indoor air temperatures within the accepted range of thermal comfort, as defined by local regulations, a certain amount of either cooling or heating might be needed. This defines the heating and cooling loads of the building within the simulation period and is calculable by Type 56a in TRNSYS.
- Depiction:

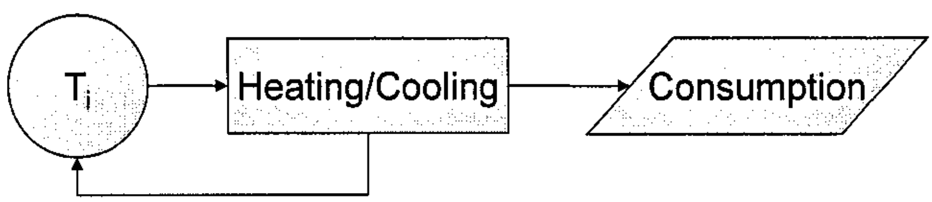


Figure 4.15 Schematic presentation of step 6

- Application: Local regulations suggest that, in order to maintain the level of thermal sensation of the users of a residential building in Isfahan within an acceptable range (from slightly cool to slightly warm), the average indoor air temperatures should be kept in a range of 18.3 to 23.7°C (BHRC 2004). This means that, in the example provided here (Figure 4.14), no cooling is needed throughout the day and the indoor environment of the building only needs some heating in the early hours of the morning (from 04:00 to 09:00 Hrs). Therefore the exact heating and cooling loads of the building for the day of this simulation, as calculated by TRNSYS, are as follows:

  Cooling load: 0
  Heating load: 36.54 kWH

On the other hand, controlling air temperatures between these two limits will eliminate the values beyond the limits from the set of actual indoor air temperatures (Figure 4.16).

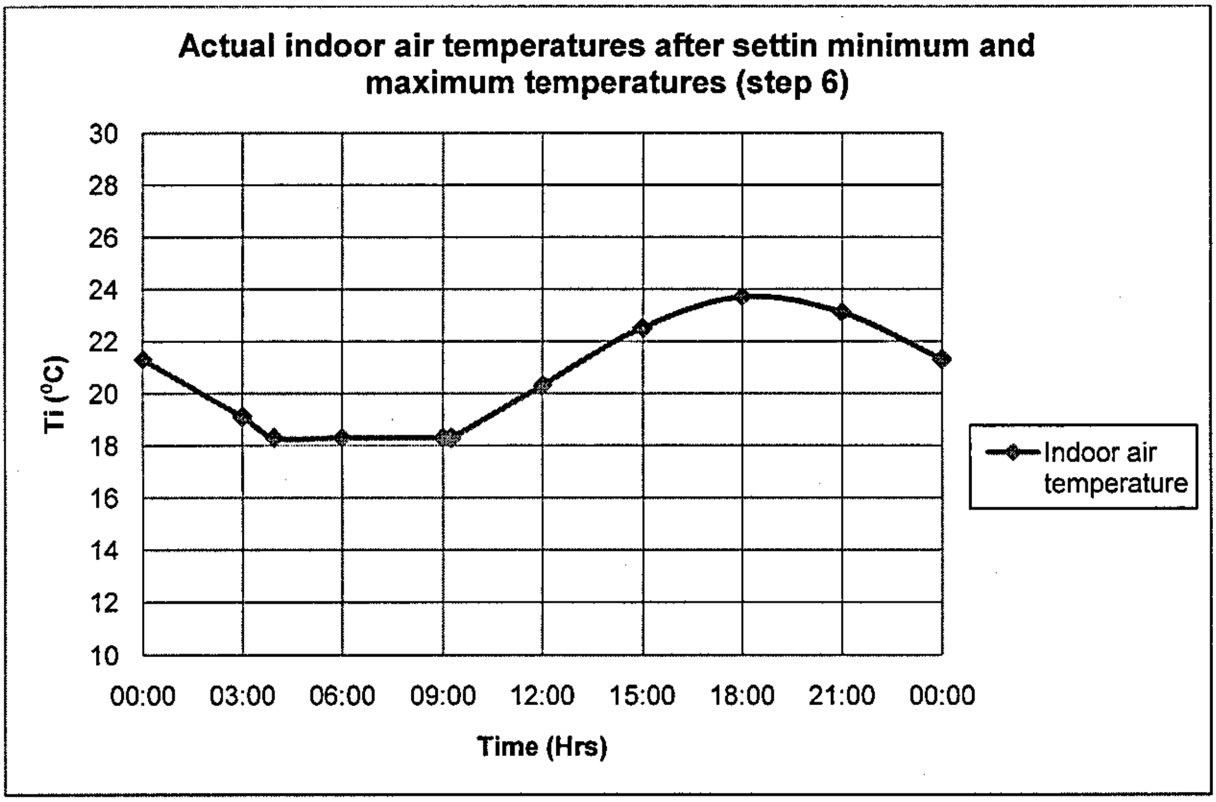


Figure 4.16 T_i after setting temperature limits

- Discussion: The results of this step provide a metric that makes different buildings comparable in regards to their level of energy consumption, which is one of the main objectives of the current research. On the other hand, by eliminating the temperatures outside thermal comfort range, changes in the energy balance on the walls (e.g. surface temperatures) is expected. A last TRNSYS simulation will provide the actual surface temperatures.

- **Step 7:**

- Program used: TRNSYS
- Input data: T_i from step 6, T_y from Step 4 and T_o from weather file
- Output data: T_s
- Description: Continuing TRNSYS simulation performed in step 6 under the set temperatures demonstrated in Figure 4.16 will result in a new set of surface temperatures (T_s).
- Depiction:

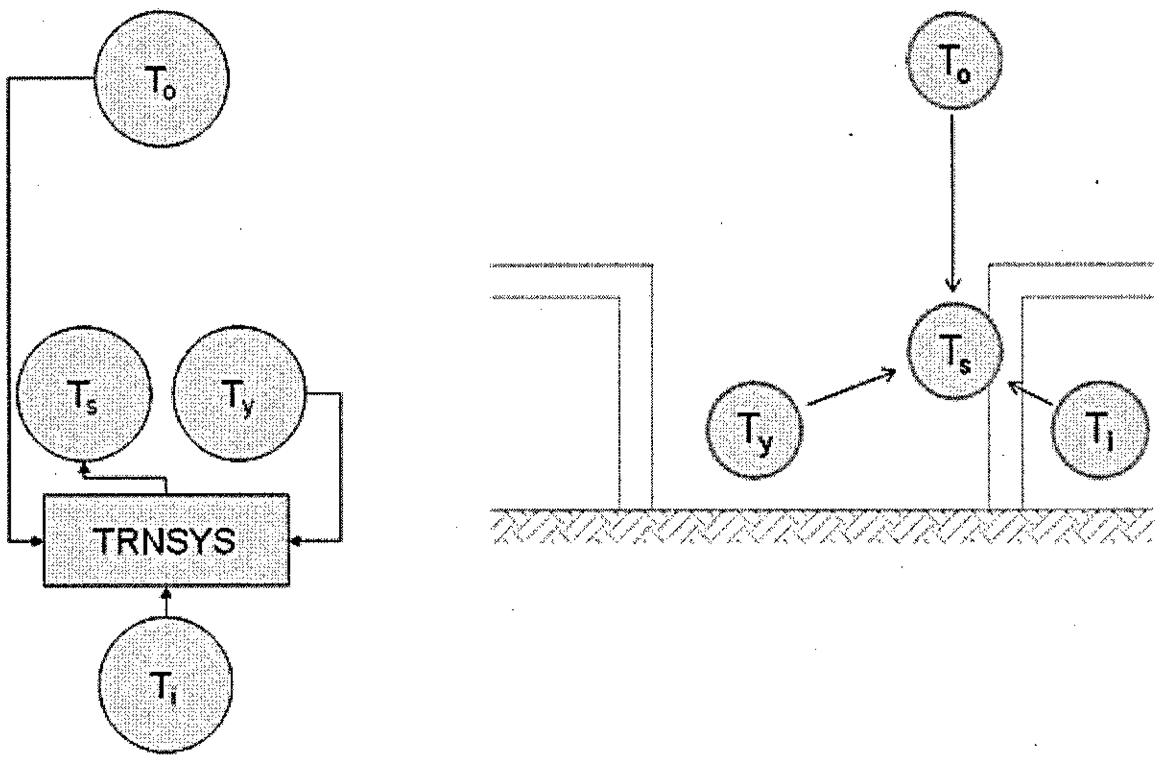


Figure 4.17 Schematic presentation of step 7

- Application: The final set of indoor air temperatures (figure 4.16) are used together with other environmental data to generate the final values for the surface temperatures across the grid cells over the outer surface of the walls surrounding the courtyard. Average of these values for one of the walls is exhibited in Figure 4.18.

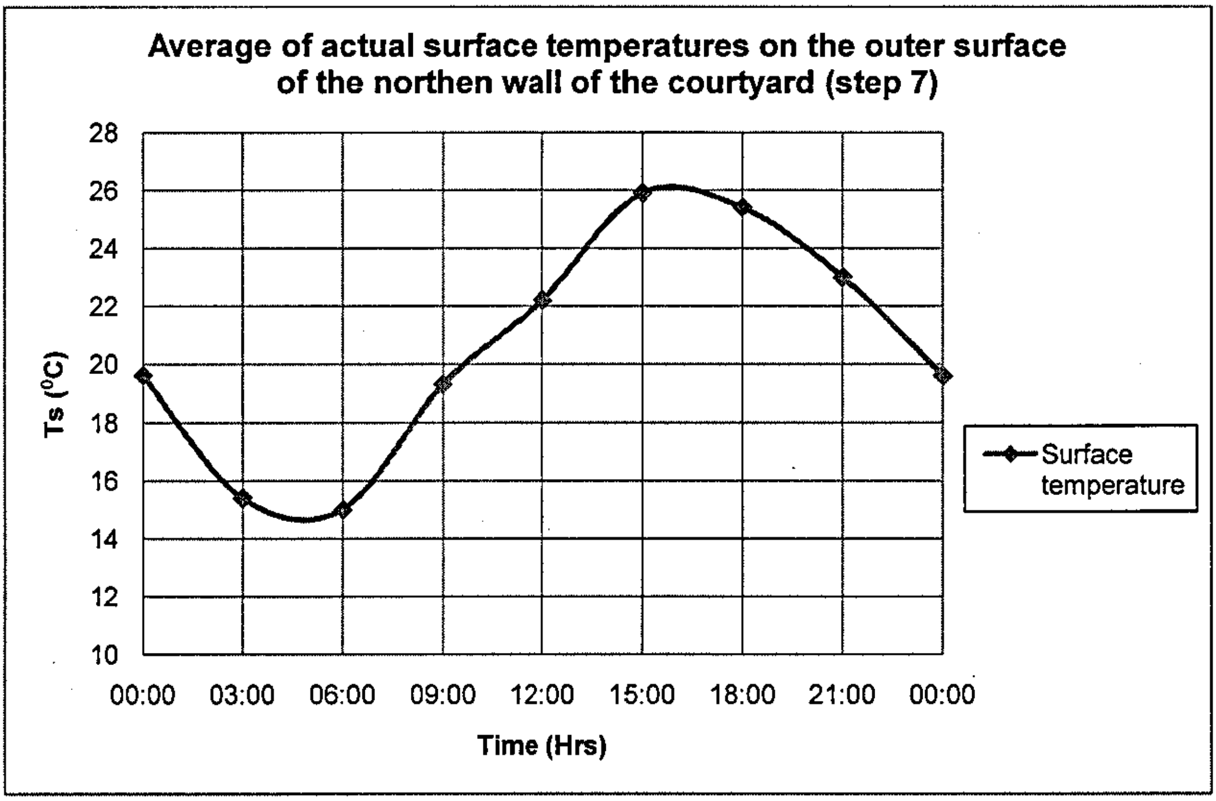


Figure 4.18 Final values for T_s

- Discussion: Final T_s values, predicted here, form one of the defining parameters for making a conclusion on the level of thermal comfort in the courtyard. They also have a significant role in predicting final values for air temperature in the courtyard, the other determining factor in the thermal comfort in the courtyard.

- Step 8:

- Program used: ENVI-met
- Input data: T_s from Step 7 and T_o from weather file
- Output data: T_y
- Description: A final run of ENVI-met simulation is needed to determine the air temperatures (T_y) of all grid cells across the courtyard. The values for the air temperature in the surrounding environment (T_o) are called from the weather

data file and the surface temperatures on the courtyard side of the walls (T_s) are entered in the data input file (*.var). Results are predicted by ENVI-met and placed in the output file (with extension *.edi) and can be exported to and plotted in a *.xls file.

- Depiction:

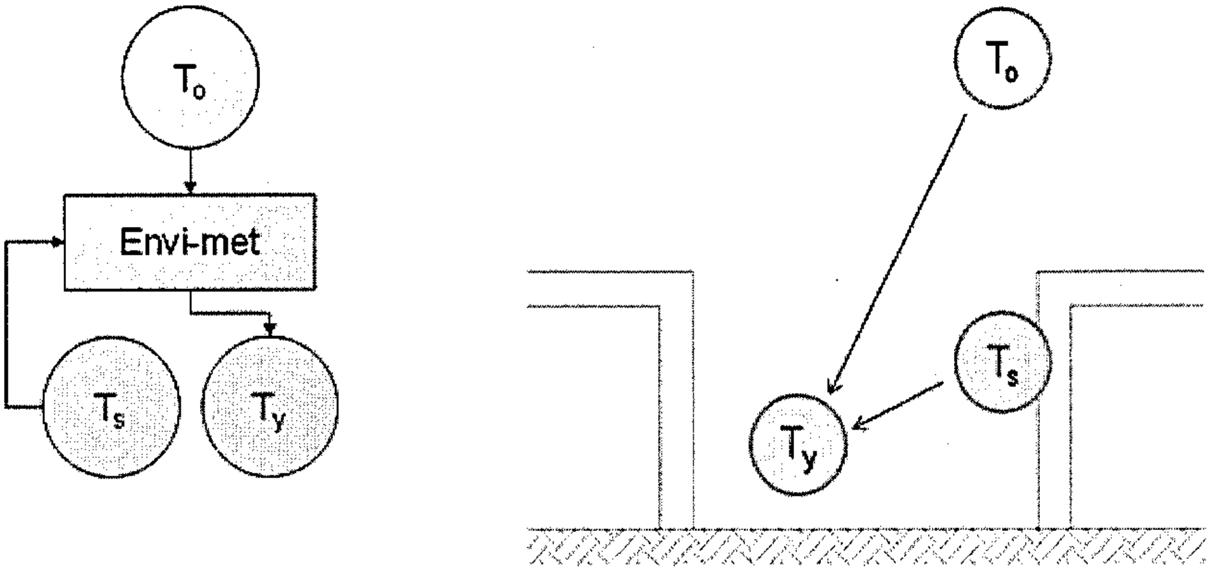


Figure 4.19 Schematic presentation of steps 8

- Application: The final set of wall surface temperatures (an example of which was presented in figure 4.18) are used together with other environmental data to generate the final values for the air temperatures across the grid cells over the courtyard. Average of these values is exhibited in Figure 4.20.
- Discussion: Final T_y values, predicted here, in addition to the T_s values, predicted in Step 7, form the defining parameters for making a conclusion on the level of thermal comfort in the courtyard and if processed through a suitable tool, are able to predict the number of thermally comfortable hours in the courtyard.

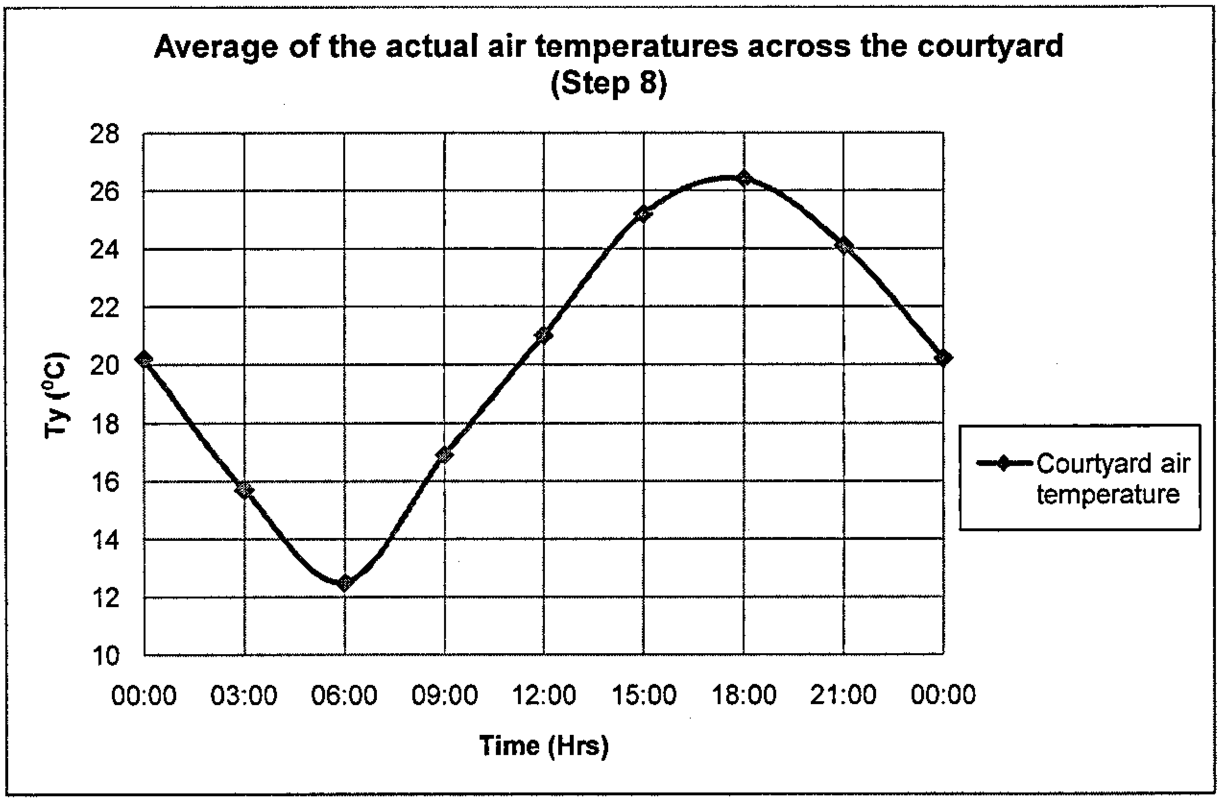


Figure 4.20 Final values for T_y

- Step 9:

- Index used: PET
- Input data: T_s from Step 7 and T_y from Step 8
- Output data: Thermal comfort in the courtyard
- Description: By calculating T_y and T_s in the environment of the courtyard, through the method described in this chapter, the only remaining unknown factors in predicting the level of thermal comfort in the courtyard are given. This means that, at this stage by using a suitable outdoor thermal comfort index, thermal sensation of the users in all grid cells across the courtyard can be predicted.

Sections 2.2.3 and 2.2.4 presented a detailed discussion on the selection process leading to adopting PET index (Höppe 1999) as the outdoor thermal comfort index used in this study. Values calculated for PET (Physiologically

Equivalent temperature) are measured in °C and represent "the temperature at which in a typical indoor setting: $T_{mrt} = T_a$; VP = 12h Pa ; v = 0.1 ms^{-1}, the heat balance of the human body (light activity, 0.9clo) is maintained with core and skin temperature equal to those under actual conditions" (Ali-Toudert 2005). Table 4.2 demonstrates how different PET values compare with PMV ranges and existing definitions for different levels of thermal perception and physiological stress.

Table 4.2 Definition of PET ranges (Matzarakis 1999)

PMV	PET (°C)	Thermal perception	Grade of physiological stress
		Very cold	Extreme cold stress
−3.5	4		
		Cold	Strong cold stress
−2.5	8		
		Cool	Moderate cold stress
−1.5	13		
		Slightly cool	Slight cold stress
−0.5	18		
		Comfortable	No thermal stress
0.5	23		
		Slightly warm	Slight heat stress
1.5	29		
		Warm	Moderate heat stress
2.5	35		
		Hot	Strong heat stress
3.5	41		
		Very hot	Extreme heat stress

• Depiction:

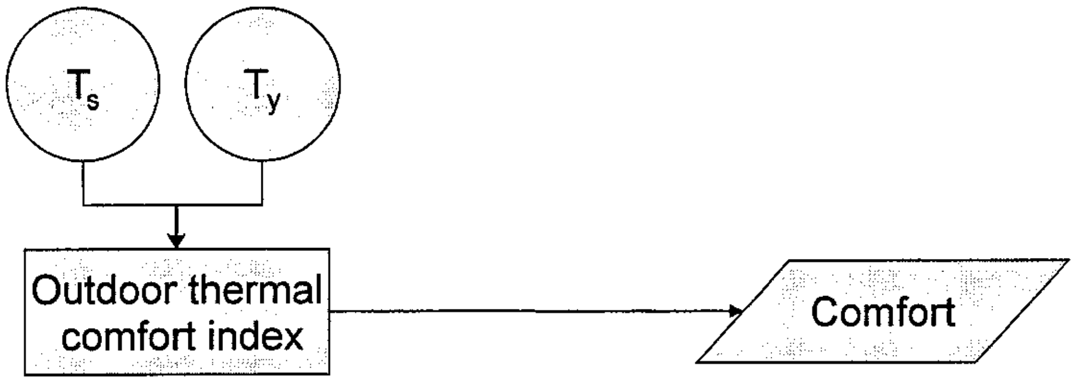


Figure 4.21 Schematic presentation of step 9

• Application: PET values for all grid cells of the simulated courtyard are calculated. Figure 4.22 shows an example of the PET values calculated for the simulated courtyard at 15:00 hrs on the day of simulations and at a height of 1m above the ground. These values span from 15 to 35 ^{0}C (from slightly cool to warm), where almost half of the courtyard is within a complete thermally comfortable range (from 18 to 23 ^{0}C).

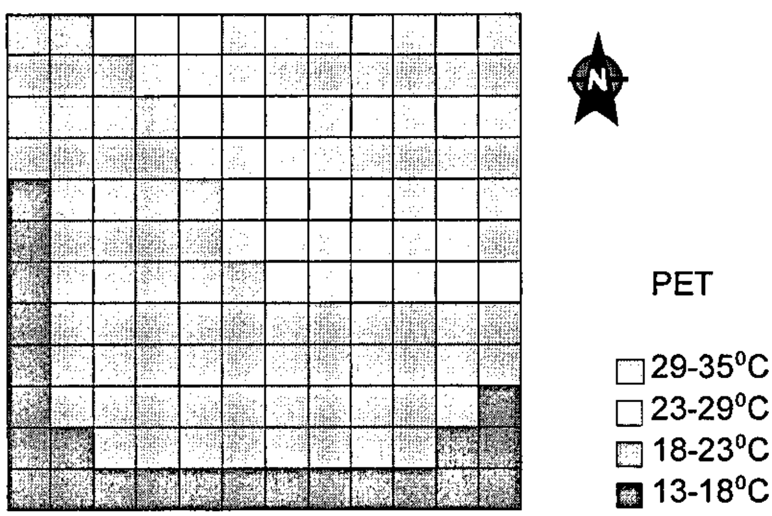


Figure 4.22 PET distribution across the plan view of the courtyard

• Discussion: The percentage of the area of the courtyard that falls within the acceptable level of thermal comfort range can be a determining factor on whether, at the specific time of the day in question, the simulated courtyard is comfortable enough to be usable. In the example provided in Figure 4.22, almost half of the area of the courtyard can provide a comfortable environment with no thermal stress. If the grid cells with a PET value between 13 to 29 ^{0}C (from slightly cool to slightly warm) are considered 'comfortable' for the activities the courtyard accommodates, about 77% of the area of the courtyard will be usable at this time. In this thesis, to judge whether a specific time of the day is thermally comfortable or uncomfortable, the following criterion was erected and adopted. If the number of useable squares of the grid (grid cells with a PET value greater than $13^{0}C$ and smaller than $29^{0}C$) equalled or exceeded one third of the total number of the squares in the grid at a given time, then that particular time will be referred as 'comfortable'. All other observation times, where there is not enough useable area in the courtyard, are considered thermally uncomfortable.

4.5 Summary

The procedure introduced in this chapter and visualised by the flowchart in figure 4.23 is aimed to offer comparable metrics between different designs for a given building. These metrics cover two general fields: the energy consumption level in the building, and the thermal comfort level in its adjacent open space. The results of this set of simulations, when compared with the ones for other alternative house/yard designs can produce a ranking on the advantage of each type from the specific point of view of energy consumption and outdoor thermal comfort. In addition, environmental, financial and cultural factors can be separately taken into account to help decision-makers on selecting the most advisable design.

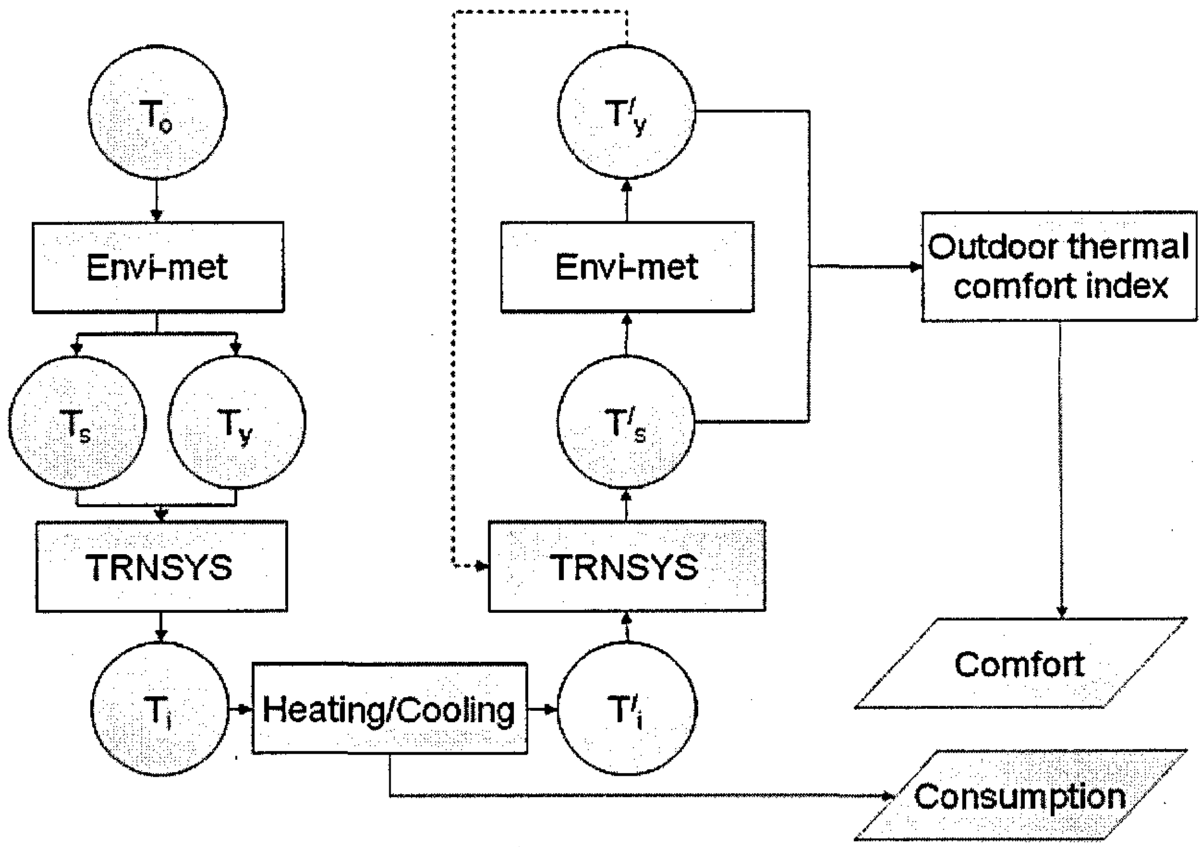


Figure 4.23 Schematic presentation of the overall procedure

A secondary contribution of the developed procedure is its potential application in future simulation programmes in order to integrate the two areas of indoor and outdoor simulations. It should be stated here that the completion of this procedure as an applicable tool highly depends on the development of the following three areas:

- A comprehensive simulation tool for outdoor climate - As discussed in the last two chapters, ENVI-met is still on its path towards completion. Some of the challenges caused by this matter were addressed in this chapter through innovative procedures. It is essential to have an outdoor simulation tool capable of tackling these problems in a more automated way.

- A reliable outdoor comfort index - Chapter 2 discussed in full detail about the ideas and theories on outdoor thermal comfort. It was mentioned there that many of the proposed indices for outdoor thermal comfort are highly dependent on the standard thermal comfort indices developed for indoor environments. The newer approaches, like the adaptive theory, seem to be a good answer to the problem of predicting outdoor thermal comfort conditions, but as long as there is no mathematical and computable indices for them, their usage will remain very difficult.
- A weighting system for compared results - The results given by this procedure cover two separate areas of comfort and energy consumption. The normal procedure in building design consists of minimising the costs of construction and maintenance of the building, while maintaining the thermal comfort indicators within an acceptable range. When talking about outdoor thermal comfort, however, the occurrence of some uncomfortable times is inevitable. Therefore, here the main concern is to maintain a balance between minimising the costs and maximising the comfortable times. An understanding between different stakeholders on the level of importance of each of these two sides is essential. Moreover, there are many other factors that determine the final design of a building, factors such as the overall cost of construction as well as maintenance, the social factors and lifestyle and local regulations. Giving a proper weight to each of these is a matter outside the concept of this research and should be dealt with according to the specific situation of each case. What this research has provided, is an approach for evaluating building energy use, together with the outdoor thermal comfort in space adjacent to the building.

5. ■ Application of the method

In this chapter an exemplary case is introduced and demonstrated in order to apply the methods and approaches in the previous chapter through this example. Application of the overall approach that has been developed constitutes the ability to offer a ranking and comparison system as one of the objectives of the research. The details of the results provided by simulation are presented and the method, through which the level of advisability of different designs could be ranked, is discussed. Such a ranking could be used as a guide for decision-making about the type of building design and urban layout that is most advisable for similar cases from the point of view of energy consumption and usability of the adjacent outdoor space from the perspective of thermal comfort.

5.1 Climatic data

It was discussed in Chapter two that the microclimatic effect of small open spaces like courtyards is more noticeable in places with higher fluctuations in diurnal temperatures. One of the main factors defining the level of temperature difference between day and night in a place is the amount of water vapour present in the air. Compared to dry air, water has a much higher thermal capacity that can play the role of a thermal regulator and therefore, the higher the relative humidity of air in one place, the lower its diurnal temperature difference.

In the present research, it seems more advantageous to consider the exemplary case in a place with higher daily fluctuations in the temperature, because larger fluctuations make it easier to study how the changes in the predicted air temperatures follow (or differ from) the changes in the outside temperature. For this reason, the weather data used in this example is the hourly data gathered and calculated for a normal year for the City of Isfahan in the hot-arid climate of Central Iran (IRIMO 2006).

Isfahan (also spelt as Esfahan) with geographic coordinates of 51°, 40′ E and 32°, 37′ N is located at an elevation of 1500 to 1600 metres above sea level in the plain of the River Zayandeh Rud , at the foothills of the Zagros mountain range in Iran. The general climate of the city is temperate with regular seasons. No geological

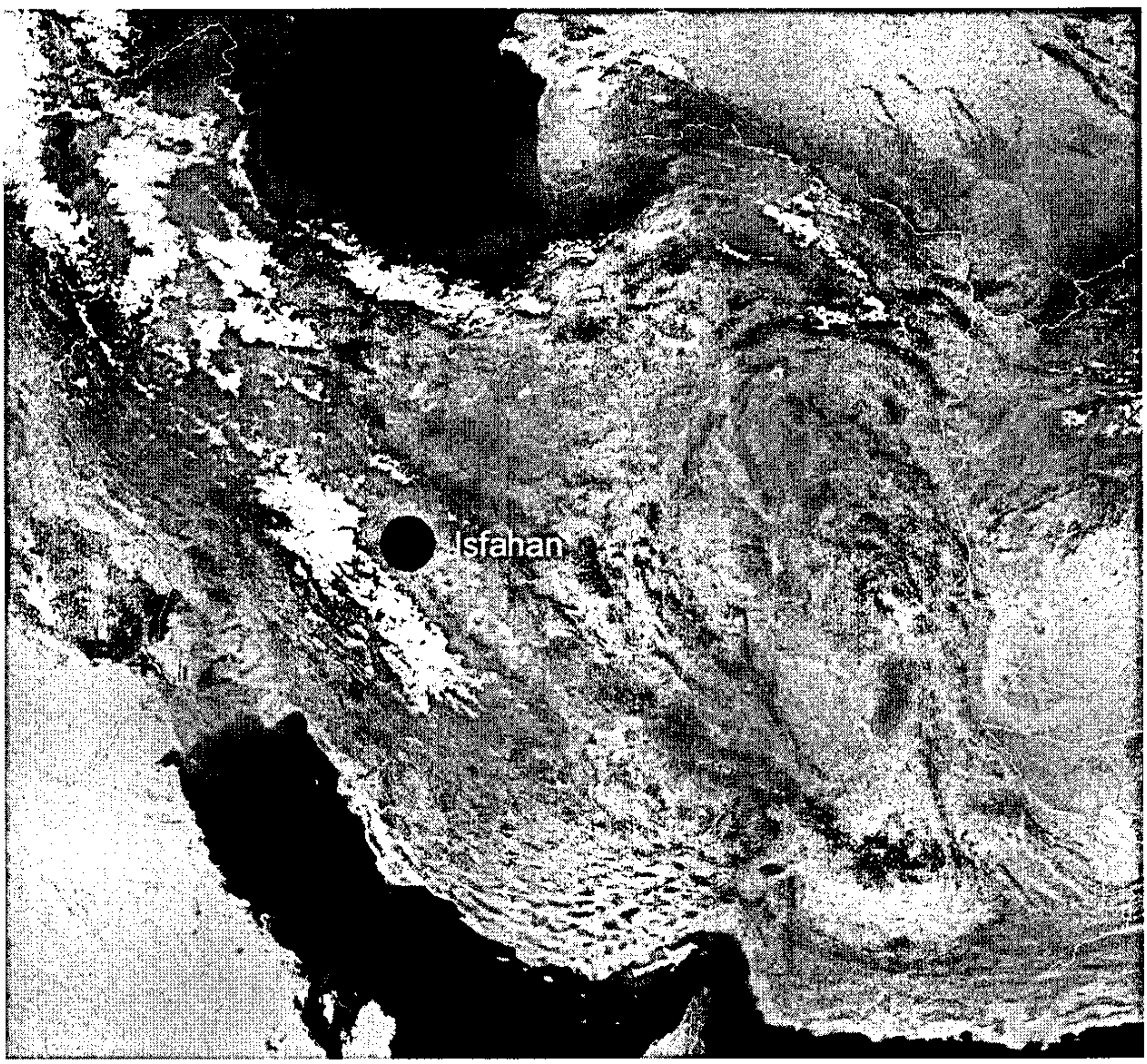


Figure 5.1 Location of Isfahan in Iranian Plateau (IRIMO 2006)

obstacles exist within 90 km north of Isfahan, allowing cool northern winds to blow from this direction.

Despite this, Isfahan is still very hot during the summer with maxima typically around 36 °C. However, with low humidity and moderate temperatures at night, the climate can be well within the thermal comfort range during summer nights. In winter, days are mild but nights can be very cold and snowfalls could occasionally occur. However, with an annual precipitation of 113 millimetres, on the whole, Isfahan's climate is classified as extremely dry.

Month	Average Sunlight (hours)	Temperature (°C)				Relative humidity (%)		Average Precipitation (mm)
		Average		Record				
		Min	Max	Min	Max	am	pm	
Jan	7	-4	8	-19	18	74	53	15
Feb	7	-2	12	-14	23	68	40	10
March	9	3	16	-11	28	57	33	25
April	8	8	22	-3	31	55	25	15
May	10	12	28	3	36	50	27	5
June	12	17	33	9	43	42	18	0
July	11	19	37	9	42	41	15	0
Aug	11	18	36	12	42	42	15	0
Sept	10	13	32	6	38	44	19	0
Oct	8	8	25	-1	33	51	24	3
Nov	8	3	17	-9	25	64	35	15
Dec	7	-2	11	-13	23	72	45	20

Table 5.1 Isfahan climatological normals for the period 1951-2005 (data from IRIMO 2006)

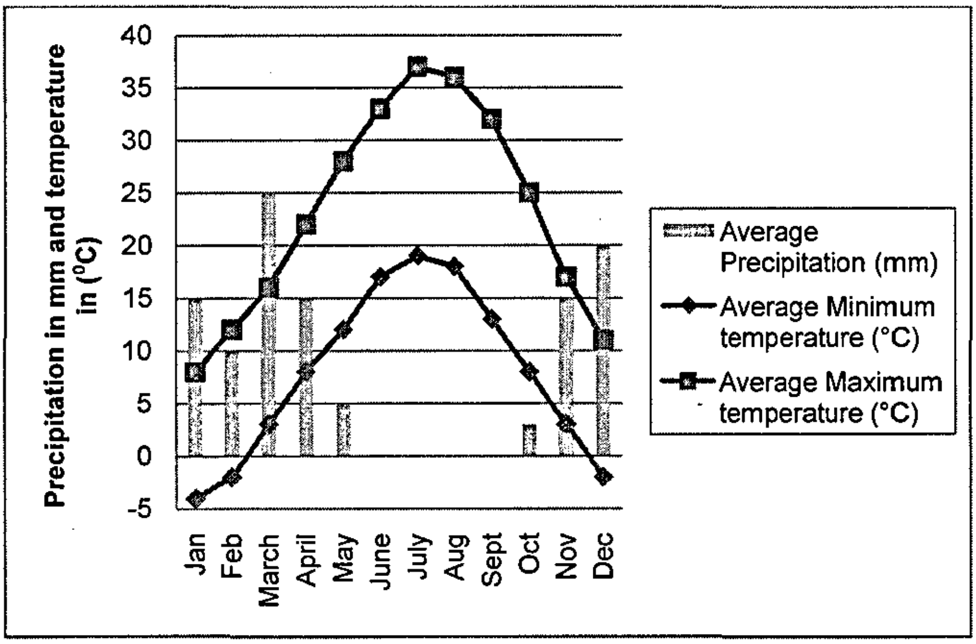


Figure 5. 2 Isfahan climatological normals for the period 1951-2005 (data from IRIMO 2006)

The data on the main characteristics of the normal weather in Isfahan (based on the data reported by IRIMO 2006) are presented in Table 5.1 and Figure 5.2.

5.2 House/yard combination types

To achieve the aim of the research (i.e. to suggest a method for making comparison between different designs available for a building from the perspective of energy consumption and thermal comfort) a set of different designs for a hypothetical building or a hypothetical block of buildings is needed. The objective of this part of the thesis is to apply the approach developed earlier to arrive at a prioritised ranking of these design types based on their energy consumption and the thermal comfort of the users of the outdoor spaces of the house.

These design types must cover the common housing styles for the area of study as well as alternative designs applicable to this specific case and since the emphasis of this study is on both indoor and outdoor thermal performance of the houses, the main factor for classification of the design styles chosen is the way these indoor and outdoor spaces are combined. In other words, the design types studied here should cover all different styles of house/yard combinations that are currently used or could be used for the hot-arid climate of Iran.

Memarian (1998) provides an extended typology of traditional Iranian houses from different points of view. One of the classification methods he uses is based on the layout of the buildings in regards to the design of their open spaces (e.g. courtyards). In his works he categorises traditional Iranian houses based on the number, size and location of the courtyards. This latter viewpoint is the one that is most related to the area of concern of the present research.

Out of 95 typical vernacular Persian houses studied by Memarian, 88 of them (93%) fall among one of the following 4 categories:

- Central courtyard houses: houses with a central open space and with all possible surrounding walls in common with a neighbouring house;

- Single standing central courtyard houses: same as above, only with no adjacent neighbours and therefore with windows on the outer wall;

- Single standing block houses: or pavilions with no adjacent neighbours and no open space in the middle;

- Front yard houses: houses with one yard on one side of the building (south side if feasible).

Heydari's study (Heydari 2000) on old and modern houses in Iran shows that these categories are still being practiced by Iranian architects today. Some of them, like single standing courtyards, have become less common, whilst others, like front yard houses, have gained enormous popularity. He also mentions two new emerging trends that were very rarely used in the tradition of Iranian architecture but their application is becoming too frequent to remain categorised as exceptions. These two emerging trends relate to the following design types:

- Semidetached houses: houses with one adjacent neighbour on one side and open spaces on other three;

- Terraced houses: or row houses, which are joined with two neighbouring buildings on two sides and have one front yard and one back yard (on the northern and southern sides of the building).

To limit the complexities found in real urban texture and to examine and compare the impact of geometry alone, a number of simplified or archetypal forms that could represent the six mentioned types are needed in this research. Results of a study on these simplified forms can then be investigated more methodically and the results can be interpreted more easily.

This type of study is not unprecedented. Martin and March (1972) have developed a similar system by choosing and simplifying six archetypes to represent the six most common types of built forms in European and North American urban areas. Their system of choice and definition of these simplified archetypes became very popular in generic studies and were extensively adopted during the last three decades in various kinds of researches (Ratti et al 2003).

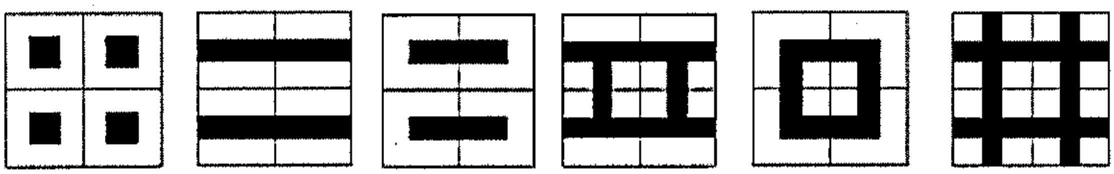
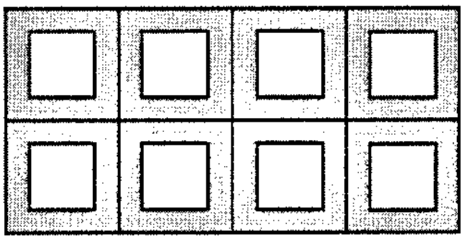


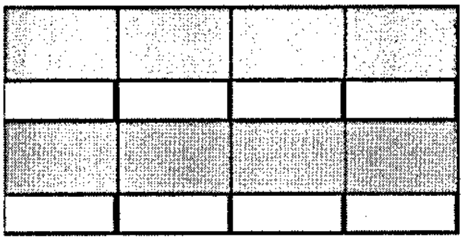
Figure 5.3 Generic urban forms, based on Martin and March (1972) From left to right: pavilions, terraces, slabs, terrace-courts, pavilion-courts and courts (Ratti et al 2003)

Although the categories introduced in Martin and March's work are not fully applicable to the Iranian housing styles and although they are initially generated for a comparative land use study between different designs, a modified version of the method used in their system is developed and adopted in the present study. The attractiveness of these generic forms mainly lies in their simple and repeatable characteristics, thus eliminating the complexities found in real urban sites and allowing for a more systematic comparative analysis of geometry and built form.

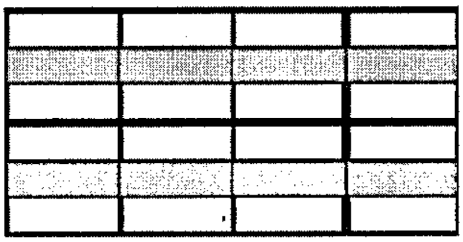
Using the design types introduced by Memarian (1998) and Heydari (2000) and the method proposed by Martin and March (1972), different designs to be studied in this thesis are defined as shown in Figure 5.4. From now on in this thesis, these different designs for house and yard combination layouts are simply called 'types'. The six types presented here are considered in an urban block of identical buildings so that the effects could be studied both in singular form and in the bigger scale of a small urban complex. The urban blocks in their initial size consist of 8 buildings in two joined rows extended in East-West direction.



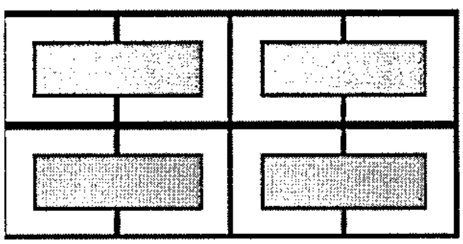
Type 1: Central courtyard



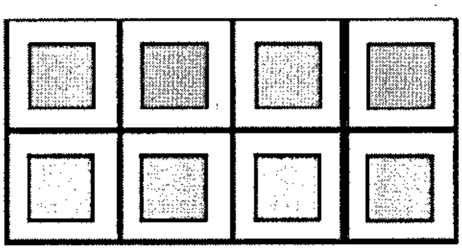
Type 2: Front yard



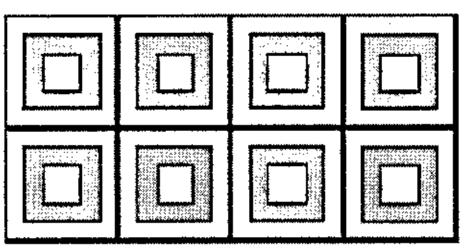
Type 3: Terraced



Type 4: Semidetached



Type 5: Detached



Type 6: Detached court

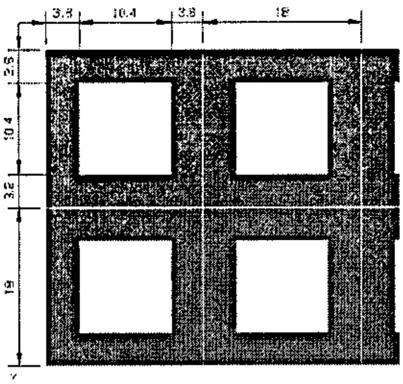
Figure 5.4 Generic urban forms used in the exemplary case

5.3 Building specifications

The Following paragraphs show how the maximum effort has been made to keep all specifications considered for all different designs mentioned in previous section) apart from their geometry) similar to each other, so that the effects observed in the simulations could be exclusively attributed to the way the building and its open space are combined.

Each type consists of 8 square plots of land covering an area of 324 m^2. In order to allow some variability in the interior design of the building and the yards and considering that designing a functional indoor or outdoor space (except for a very limited number of spaces like corridors or utility rooms etc.) in a very narrow place is almost impossible, the minimum acceptable width for any indoor or outdoor space is fixed at 3 m. The following figures show that based on this limitation, some of the six types in the example need to be built in two storeys, provided that the total area of the indoor space and consequently the volume of the indoor air are kept constant. This is an important issue because, in order to be able to make a comparison between different types in regards to their energy consumption, the volume of the air that needs to be heated or cooled must be kept equal. Therefore, if the nature of the layout of a specific type does not permit achieving the desired air volume in one storey, the total area of indoor space will be distributed in two storeys.

As seen in these figures, the area of the land occupied by one house in each of the types is kept equal to 324 m^2 and the total floor area equal to 216 m^2 ($\pm$0.3 m^2). With a ceiling height of 3 m, the total air volume inside all types will be almost identical and equal to 648($\pm$1) m^3.



Type 1 – Central courtyard

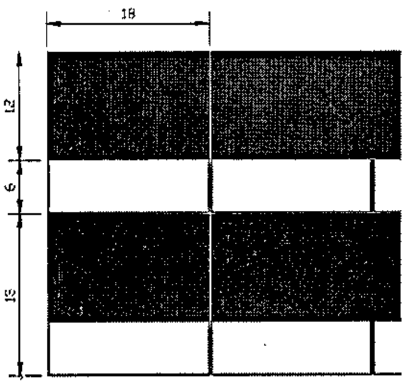
Land area= 324 m^2

Built area = 215.84 m^2

Number of storeys = 1

Floor area = 215.84 m^2

Indoor Air volume = 647.52 m^3



Type 2 – Front yard

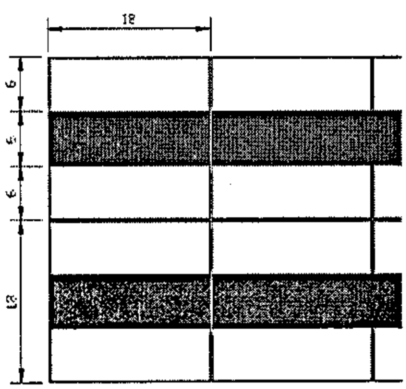
Land area= 324 m^2

Built area = 216 m^2

Number of storeys = 1

Floor area = 216 m^2

Indoor Air volume = 648 m^3



Type 3 – Terraced

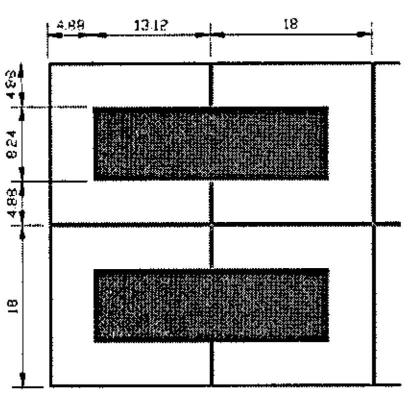
Land area= 324 m^2

Built area = 108 m^2

Number of storeys = 2

Floor area = 216 m^2

Indoor Air volume = 648 m^3



Type 4 – Semidetached

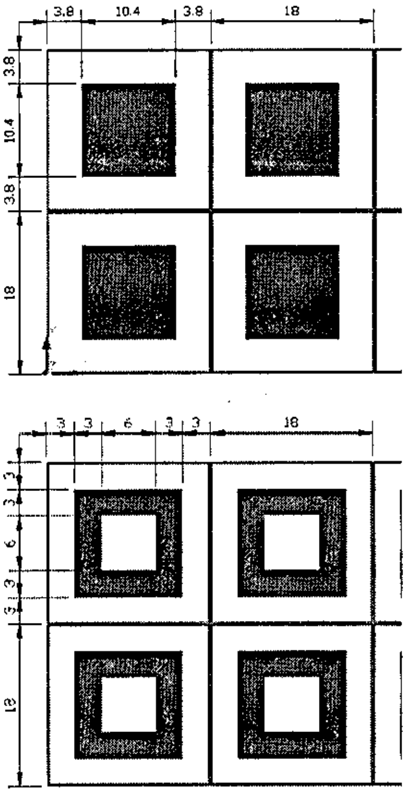
Land area= 324 m^2

Built area = 108.11 m^2

Number of storeys = 2

Floor area = 216.22 m^2

Indoor Air volume = 648.65 m^3



Type 5 – Detached

Land area= 324 m^2

Built area = 108.16 m^2

Number of storeys = 2

Floor area = 216.32 m^2

Indoor Air volume = 648.96 m^3

Type 6 – Detached court

Land area= 324 m^2

Built area = 108.11 m^2

Number of storeys = 2

Floor area = 216.22 m^2

Indoor Air volume = 648.65 m^3

Figure 5.5 Dimensions of different design types

Figure 5.6 provides a three dimensional presentation of the types mentioned in Figure 5.5. As seen in this figure, design types 1 and 2 consist of one storey buildings and the rest of the types are formed in two storeys to keep the total floor area and air volume of all types identical. These three dimensional models will be defined in both ENVI-met and TRNSYS according to the method presented in Chapter 4 and results will be discussed.

The percentage of the windows used on each wall is decided by the local regulations according to the national targets for reducing energy consumption of residential buildings in Iran (INBC19 2000). According to these regulations, the window area on a wall facing south must not exceed 50% of the total surface area of that wall. The

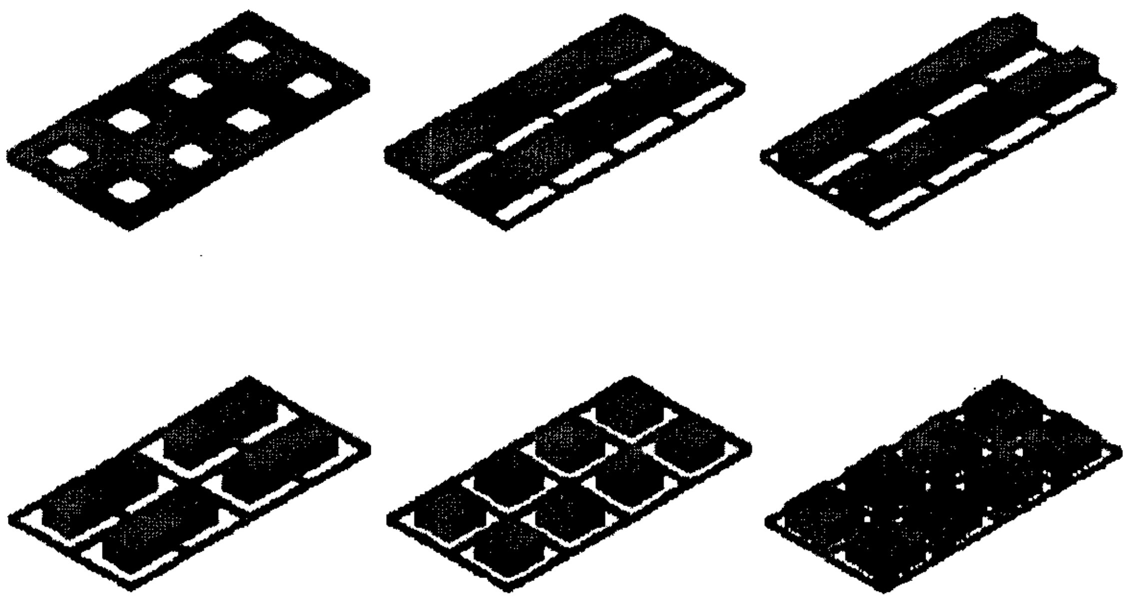


Figure 5.6 Three dimensional presentation of the 6 types over urban area

corresponding figure is equal to 80% for a Northern wall and 15% for the walls facing East or west. These maximum values have been used in all simulations presented here.

The areas of the individual windows are also kept within the same building codes (INBC19 2000). Based on this standard, and assuming a fixed height of 1.5 m for all windows, the width of the windows simulated on each of the North, South, East and West facing walls will be 3, 2 and 0.5 metres respectively. All these windows are double-glazed with a total U-value of 2.8 $Wm^{-2}K^{-1}$ with convective heat transfer coefficient of 3 and 18 $Wm^{-2}K^{-1}$ for front (inside surface) and back (outside surface) respectively. Window frames are also considered to have an area equal to 20% of the overall area of the windows with a U-value of 2.27 $Wm^{-2}K^{-1}$ and a solar absorptance of 0.6.

INBC19 (2000) also suggests the use of a chart for the size of fixed shading devices for the windows on each wall. According to this chart, the South facing windows with the above size will have an overhang and two side wingwalls all of 0.5 m depth. All North facing windows will have only one 0.3 m deep wingwall on the side towards west. Also Eastern and Western windows will only have wingwalls, on the side towards South. These wingwalls will be 0.5 deep.

All external walls will consist of a 0.24 m wide layer of brick, 0.1 m of insulation and a plaster layer of thickness 0.015 m. Walls in common between neighbours will be separated by a 0.2 m gap. Thermal characteristics of these layers are summarised in table 5.2:

	Conductivity ($Wm^{-1}K^{-1}$)	Capacity ($Whkg^{-1}K^{-1}$)	Density (kg/m^3)
Brick	0.889	0.278	1800
Insulation	0.04	0.222	40
Plaster	1.389	0.278	2000

Table 5.2 Thermal characteristics of the layers of the external walls

The remaining conditions for which all outdoor simulations were run consist of the following factors:

Ground Reflectance: 0.2

Ground slope: 0

Wind velocity: 0.1 m/s (constant)

Relative humidity: 50% (constant)

Atmospheric pressure: 1 At (constant)

Density of air: 1.2 kg/m^3

Specific heat of air: 0.281 Wh/kgK

Heat of vaporisation of water: 0.682 kWh/kg

5.4. Results

After describing the procedure of combining the application of two already available simulation tools, ENVI-Met (for investigating the thermal performance of the buildings in connection to the conditions and of the surrounding natural and built environment) and TRNSYS (to study the thermal conditions of indoor living spaces), in Chapter 4, the present chapter has, so far, presented the initial data needed to apply this procedure to the process of decision-making in the early stages of designing the layout of a real building or neighbourhood. This was done through covering the details of the data needed for running these simulations for a hypothetical setting and under sample weather conditions.

This data, when processed through the integral procedure of indoor and outdoor simulation, as introduced in Chapter 4, can provide the information and the results needed to suggest a ranking of the different designs based on their indoor and outdoor thermal performance. This section will discuss these results (for energy consumption of different types as well as the level of thermal comfort sensed in their adjacent open spaces) and proposes ways for generalisation of the method based on the considered exemplary case.

5.4.1. Energy consumption in the buildings

A combination of two simulation programs, ENVI-met and TRNSYS, was used (based on the method described in Chapter 4) to calculate the amount of energy consumed in each type of the design layouts introduced earlier in this chapter. The results of these calculations are presented in the comparative diagrams presented in following pages.

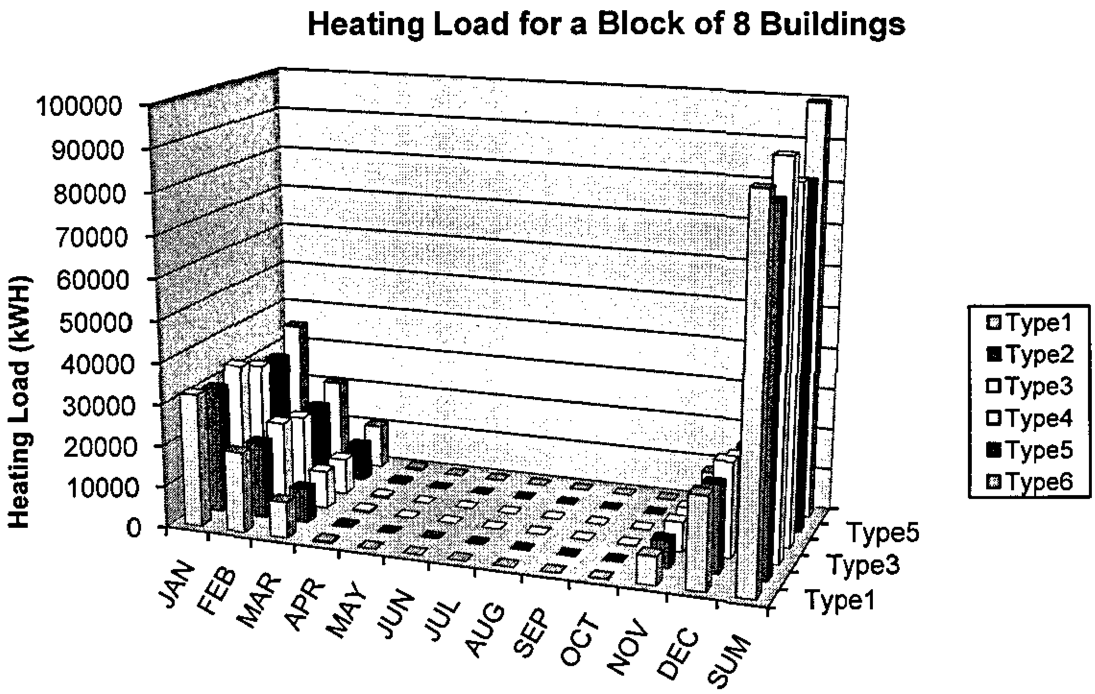


Figure 5.7 Monthly and yearly heating loads of different types

Figure 5.7 demonstrates the significant impact of the design layout on heating energy demands of the buildings with similar specifications. In the example presented in this chapter, Type 6 (Detached court house in figure 5.4) needs about 20% more energy for heating up the building in comparison to type 5 (detached house). This might be attributed to the smaller area of exposed surfaces to the air in type 6, compared to type 5. To investigate this theory, the 'surface to volume ratio' of all types are calculated and their relation with the level of heating energy consumption is studied. As an example, the method for calculating surface to volume ratio for type 1 is presented here:

- Surface area:

The urban block Type 1, presented with its dimensions in Figure 5.8, consists of 12 external walls, each with the dimensions 18 x 3 metres. There are also a total of 32 internal walls (courtyard walls) with the dimension 10.4 x 3. The roof area of each house is also equal to 215.84 m^2 (Figure 5.5).

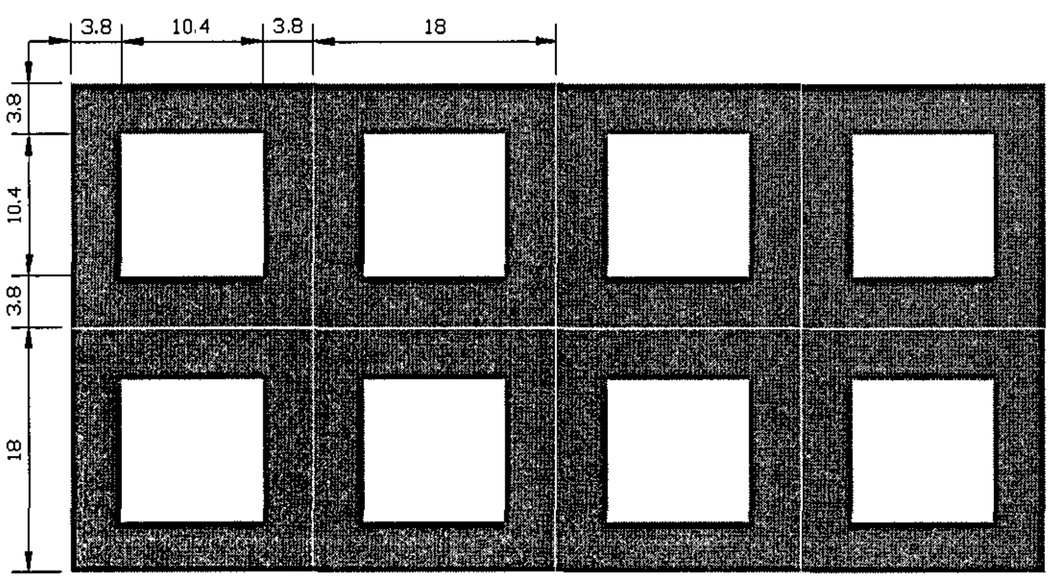


Figure 5.8 Dimensions of Type 1

Therefore the total area of the outer surface of the block is:

12x18x3+32x10.4x3+8x215.84=648+998.4+1726.72=3373.12 m^2

The total air volume inside the buildings of the block can also be determined as 8 times 647.52 m^3 (Figure 5.5):

8x647.52=5180.16 m^3

and therefore, the total surface to volume ratio of the block is equal to:

$3373.12/5180.16=0.65\ m^{-1}$

Figure 5.9 shows this ratio for all types in the exemplary case in comparison to the total heating load as predicted in Figure 5.7.

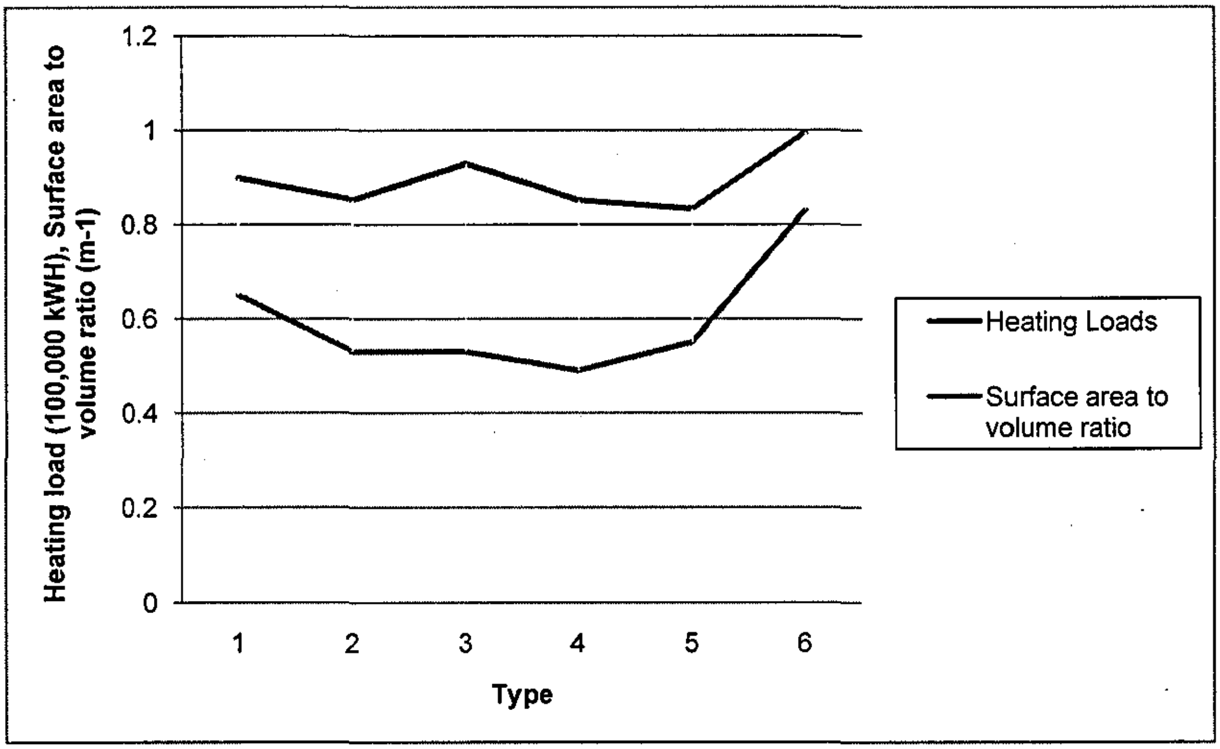


Figure 5.9 Comparative study of the effect of 'surface area to volume ratio' on heating loads

It is a rarely debated rule of thumb that "the higher the surface area to volume ratio of a building, the more the energy consumption of that building". Comparing the general trends of the two diagrams in Figure 5.9 demonstrates that this rule, up to a high extent, is relevant to the example discussed here. However, the diagram also shows that this rule, on its own, is not a completely accurate way for ranking the energy demands of different designs at least when considering heating demands of buildings. For example, although type 5, in Figure 5.9, shows a higher surface area to volume ratio in comparison to type 4, its heating load is, in fact, slightly smaller than that of type 4. This provides further evidence on the necessity of the integrated simulation of indoor and outdoor environments of a building, to which a method was introduced in this thesis.

Cooling loads of the buildings, also, show the great impact of the design layout on energy consumption of a house (Figure 5.10).

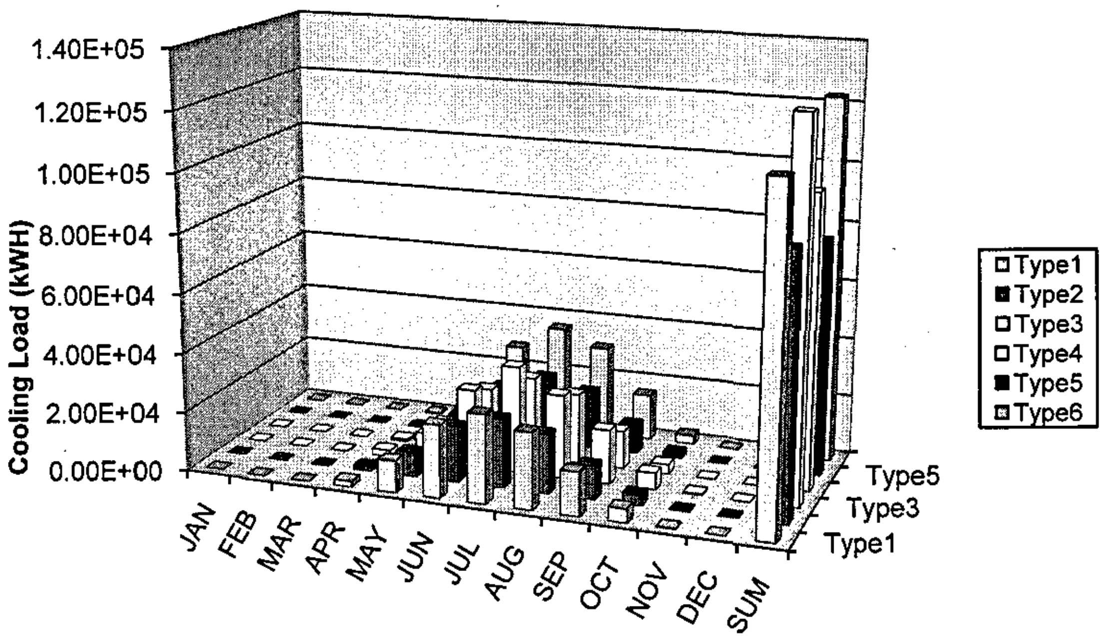


Figure 5.10 Monthly and yearly cooling loads of different types

In fact, the effects of house/yard configuration on energy consumption of buildings is, arguably, much more obvious in warmer times of the year. The biggest consumer of cooling energy, as demonstrated by figure 5.10, is Type 3 (terraced housing), which in comparison to the most energy efficient type in summer (Type 5), has an energy consumption of about 60% higher. This is a clear indication of the importance of the subject of this thesis (i.e. integrated design of indoor and outdoor environment of the building for best energy efficiency), particularly in places with longer and harsher hot seasons.

Comparing these results with the surface area to volume ratio of different types shows, one more time, that considering only surface area to volume ratio is not an accurate way of understanding the level of energy consumption in a building in comparison to another.

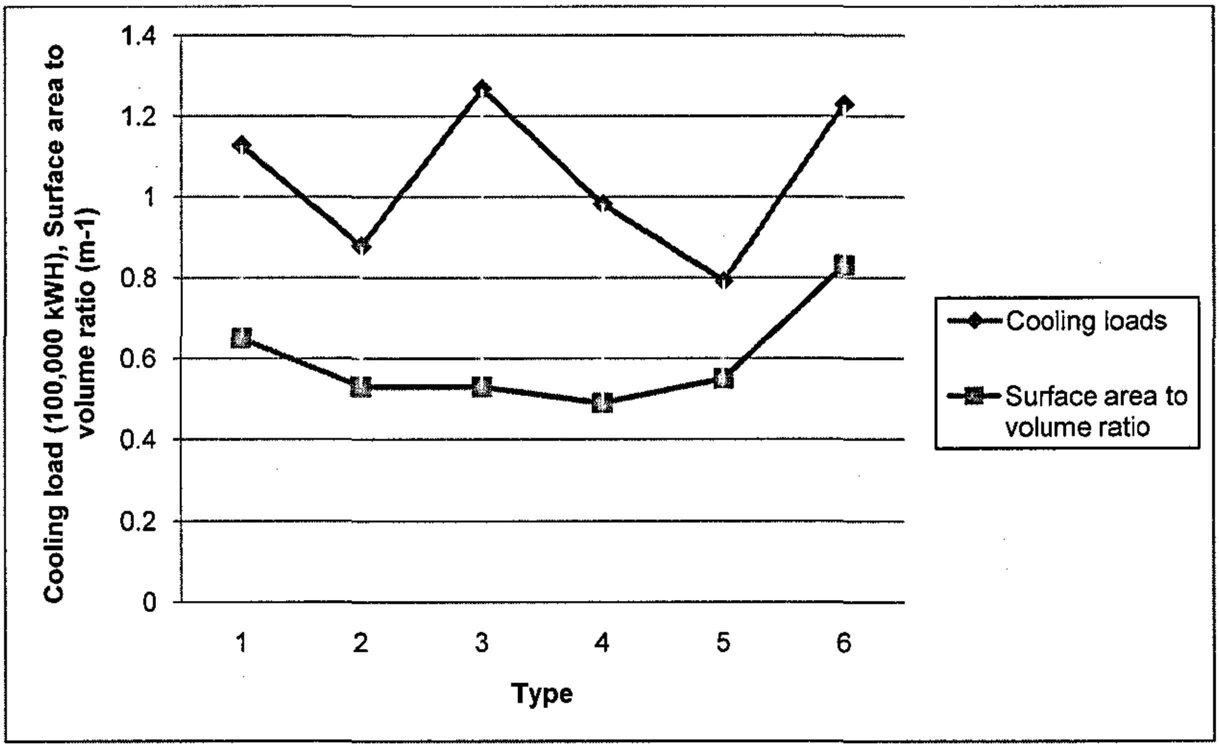


Figure 5.11 Comparative study of the effect of 'surface area to volume ratio' on cooling loads

Now, by adding the total cooling and heating demands of each block and averaging for a single house, the average early energy consumption of each type is calculated (Figure 5.12). This values show that, if designed properly, a house in the studied case can save up to 10 MWh energy in a year. That is equal to 35% of the total energy used in some of the studied types. The potential of each type in energy saving could be used as a measurable metric when comparing with other types and is one of the results sought by this exemplary case to allow selecting one of these types as the most advisable type for these specific conditions.

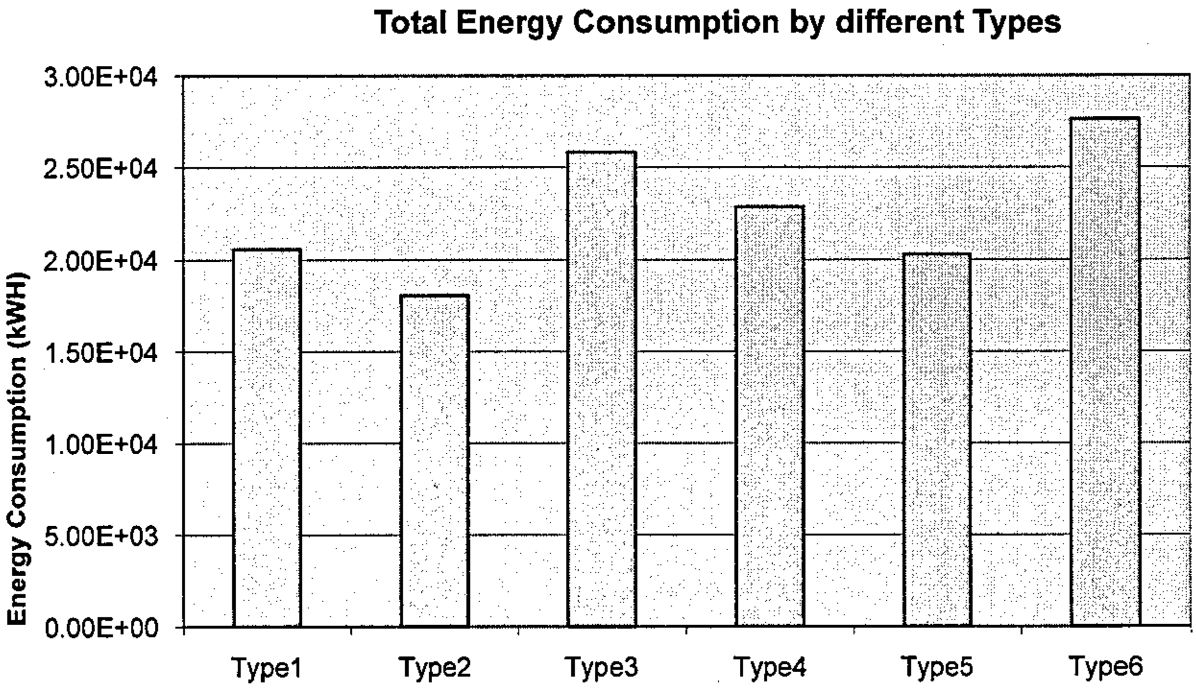


Figure 5.12 Average yearly energy consumption per house

5.4.2 Thermal comfort in the open spaces

The method for assessing the level of thermal comfort in an open space adjacent to a building was explained in Chapter4. Using this method for the building types in the current exemplary case will offer a comparable metric, through which the buildings in question can be ranked according to the level of thermal comfort of the users of their open spaces. Figure 5.13 shows the total yearly number of thermally comfortable hours for each type compared to the number of thermally comfortable hours outside the built area.

This diagram shows that, for example, when comparing types 5 and 6, it is observed that only through selecting the right type of combination of building and yard in a house, more than 1000 hours (about 12% of the whole duration of a year) is added to the number of thermally comfortable hours outdoor. This means that in comparison to Type 5, private outdoor grounds of Type 6 are usable by the occupants for a further 12% of the time. In cultures, like Iranian culture, in which people value outdoor family activities in the privacy of their enclosed yards or courtyards, this can be considered as a defining factor, when selecting between different design types.

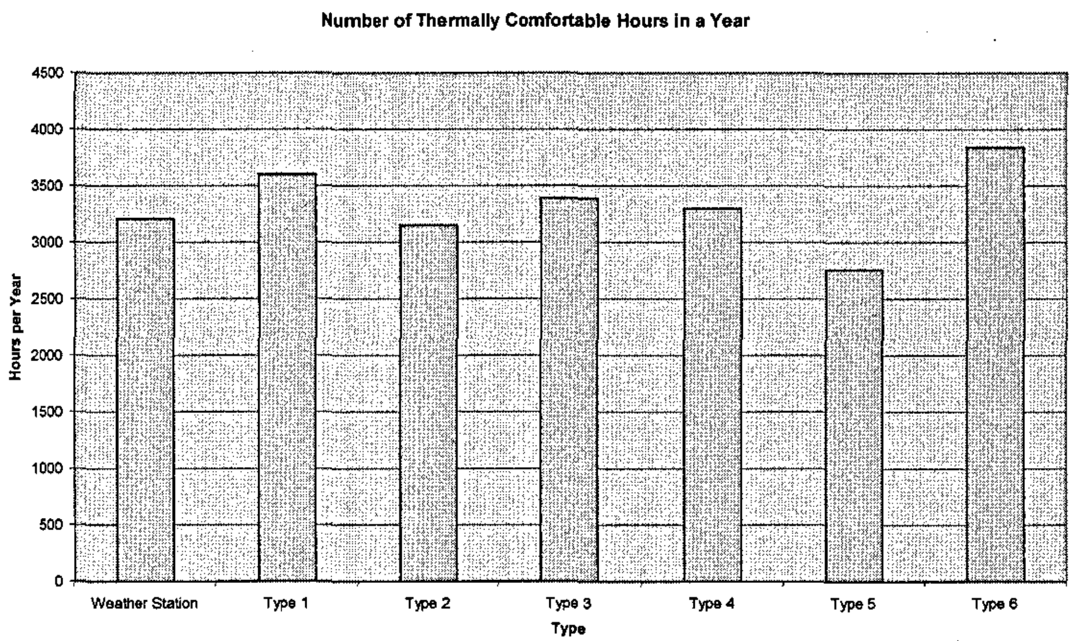


Figure 5.13 Comparative outdoor thermal comfort of all house types

5.4.3. Decision-making

The knowledge acquired through this process on the advantages and disadvantages of different design types can form the basis for the professional advice of an expert of energy and thermal comfort on the type of design layout that is more suitable for a specific house or a housing development. This knowledge, however, is not enough on its own and many other factors, which are out of the prospect of the current thesis, must be considered when making the final decision on the design of a house or a series of houses.

For example, the effect of the lifestyle of the occupiers and users of a house cannot be ignored when deciding about the nature and characteristics of the outdoor living spaces of a house. In Iran, for instance, the idea of having a private outdoor space that serves as one of the main family rooms of the house has always been an important part of residence traditions. This will act in favour of those 'types' that provide more privacy (e.g. central courtyard house) when the choice between different types is given.

Cost effectiveness is another factor that has to be considered in this matter. Different design types, essentially, mean different construction costs and most probably different maintenance costs too. Consideration of this one fact could mean a major change in the order of the previously mentioned rankings if a house that is found to be more energy efficient or thermally more comfortable, imposes a substantially more expensive option on the client.

Environmental issues also must not be forgotten. Short-term and long-term impacts of the building on its environment or environment's impact on the house can make a certain design type unfeasible. For example, in a country with too many rainy days during a year, the nature and intensity of utilisation of the outdoor space of a house is much more limited in comparison with a place with large numbers of sunny days. In the same way, the air pollution can restrict the potential of the most skilfully designed courtyards for being used as an outdoor living space.

Therefore, in a real decision-making process many experts should be present to assess all different possibilities from different viewpoints. The matter under the focus of this study is to assess the advisability of a house design in regards to its energy consumption and the thermal comfort offered by its open space. Even this 'advisability' could be interpreted differently in different cases. The weight given to each side of these considerations (i.e. energy consumption or thermal comfort) can vary substantially from case to case and from place to place. In some cases, for reasons such as high prices of energy, the outdoor thermal comfort argument could even sound irrelevant. In some other cases, however, because of the lifestyle of the household, usability of the yard or courtyard could become of the same importance as energy consumption or even more important.

Just to demonstrate an example of the procedure, here an equal importance for both sides of this problem (energy consumption and thermal comfort) is assumed. As a comparable measure between different types that covers both energy consumption and outdoor thermal comfort, 'advisability' is defined as follows. Advisability is calculated by adding up the percentage of the improvement that each type can offer in comparison to the worst option in both energy consumption and outdoor thermal comfort.

In this example, the building design marked as 'Type 6' showed the highest energy consumption among all types. The amount of improvement in energy saving that each type can offer, when compared to Type 6, is demonstrated in Figure 5.14.

Further to the answers derived for the specific design case, presented in this example, as to which of the defined archetypes can be most suitable in this case, the results obtained from this comparison can also be interpreted as a general guide for the overall layout of small residential buildings in this climate and in similar places.

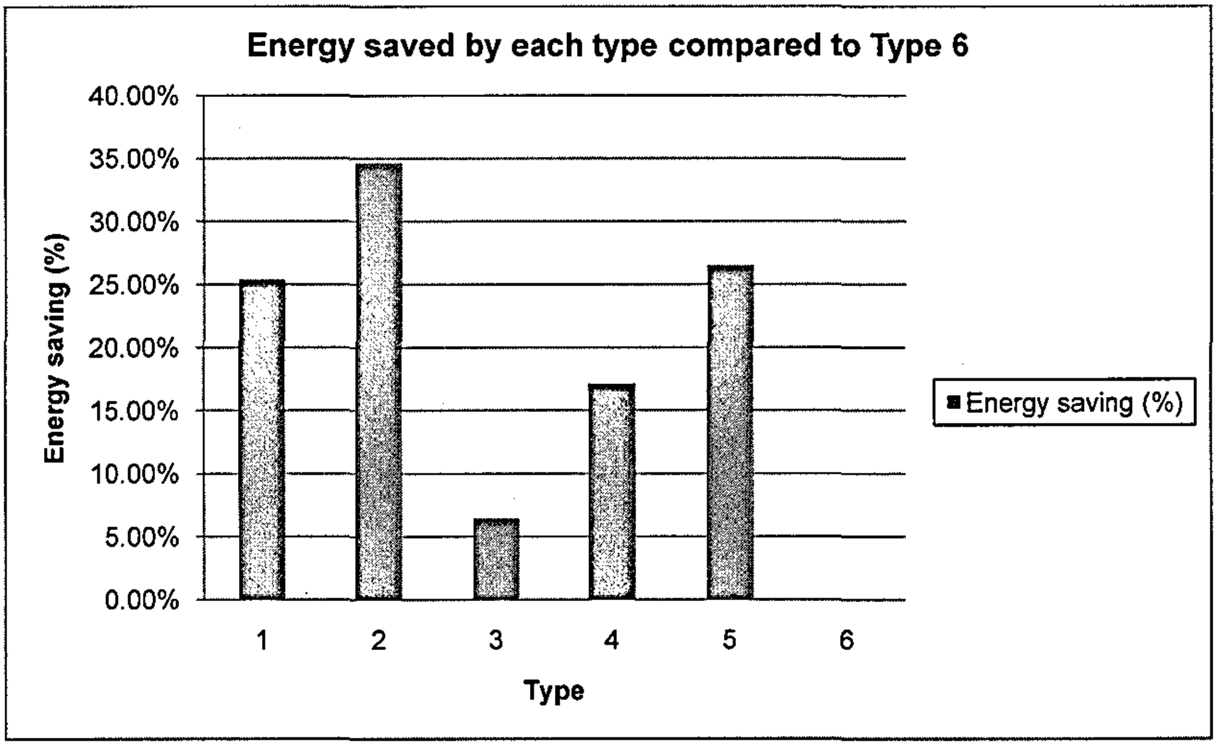


Figure 5.14 Yearly energy consumption improvement offered by each type, compared to Type 6

Diagram presented in Figure 5.14 clearly shows that, in this climate, small houses that are built in two storeys (Types 3 to 6), if not designed carefully, could in general consume more energy compared to single-storey houses that contain the same volume of air (Types 1 and 2). Apart from the reduced amount of natural heat gain and heat loss from and to the ground surface (because the entire upper storey is built on occupied spaces with similar indoor temperatures), two-storey buildings also have a larger window area (twice that of a single-storey building on similar surfaces) that could contribute to a weaker environmental control.

Also in each category (single-storey houses and two-storey houses), a direct relationship is observed between the deepness of the building plan and its energy saving. This means that, in climates like that of Isfahan, long and narrow plans are less favourable when wider options are available.

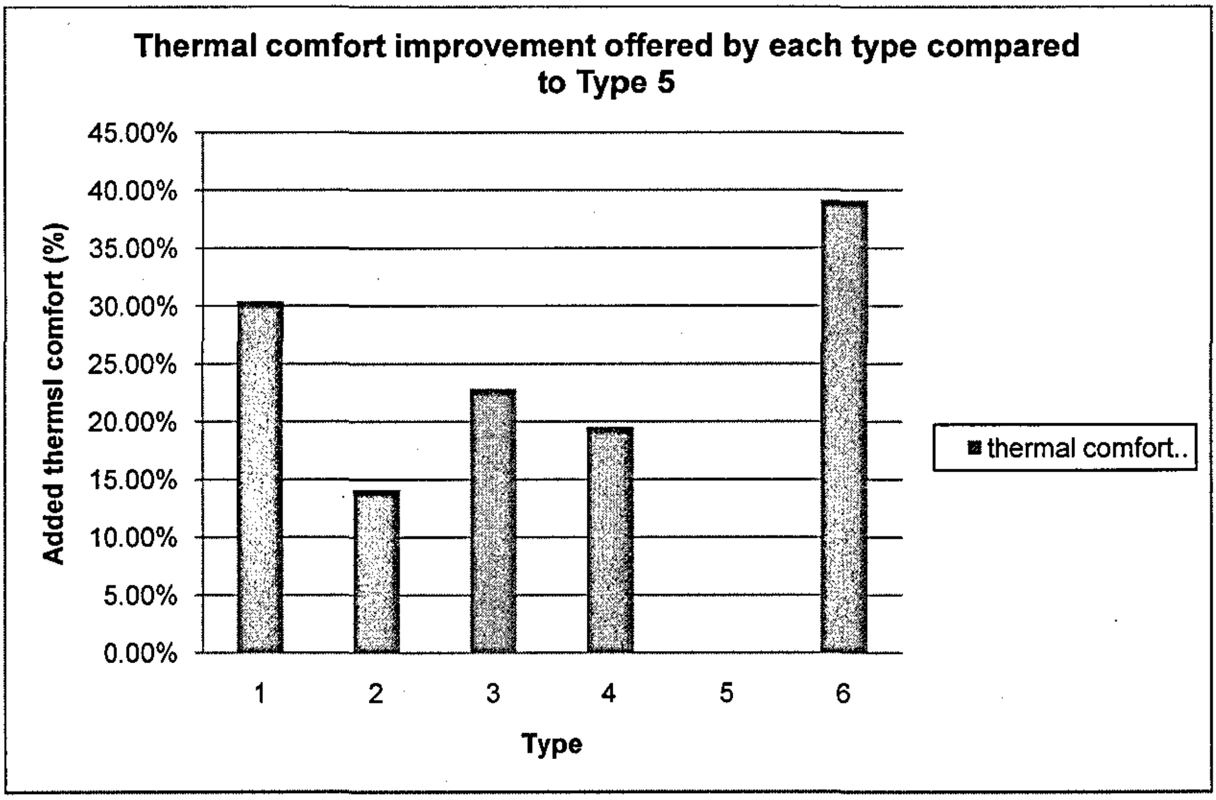


Figure 5.15 Yearly improvement in the number of outdoor thermal comfort hours compared to type 5

On the other hand, when looking at the thermal comfort offered by each layout type, Type 5 provides the lowest number of thermal comfort hours in its open space among all types. The amount of improvement in outdoor thermal comfort, offered by each of the other types, is plotted in Figure 5.15.

Analysing these results reveals that, in this climate, the two factors that define which type's open space is more desirable than the other are the 'enclosure' level of the open space and its 'flexibility'. As seen in the diagram, Types 1 and 6 (row central courtyard house and detached central courtyard house) that have a courtyard enclosed on all four sides by the house building offer a much higher level of thermal comfort compared to other types. Flexibility of the open space (i.e. offering different areas with distinct different level of solar irradiation) makes the open space usable in a much wider variety of hours. Sunnier corners accommodate for colder times of the day (or year) and areas protected from the sun make the open space a pleasant place for hot hours. For example, the main difference between Types 2 and 3 is the fact that Type 2 has only one south-facing front yard, whereas, in type 3 a backyard is also provided for the house.

When the two values from these two diagrams are combined for each type, the value of 'advisability' of each type from the perspective of energy consumption and thermal comfort is defined. Figure 5.16 presents the level of advisability of each of the design types introduced in this example for the conditions defined by the local weather.

As figure 5.16 demonstrates, Type 1, central courtyard house is the most advisable design for the conditions of this example, followed closely by Type 2 (front yard house). Fully detached block houses (Type 5), on the other hand, prove to be the least advisable alternative.

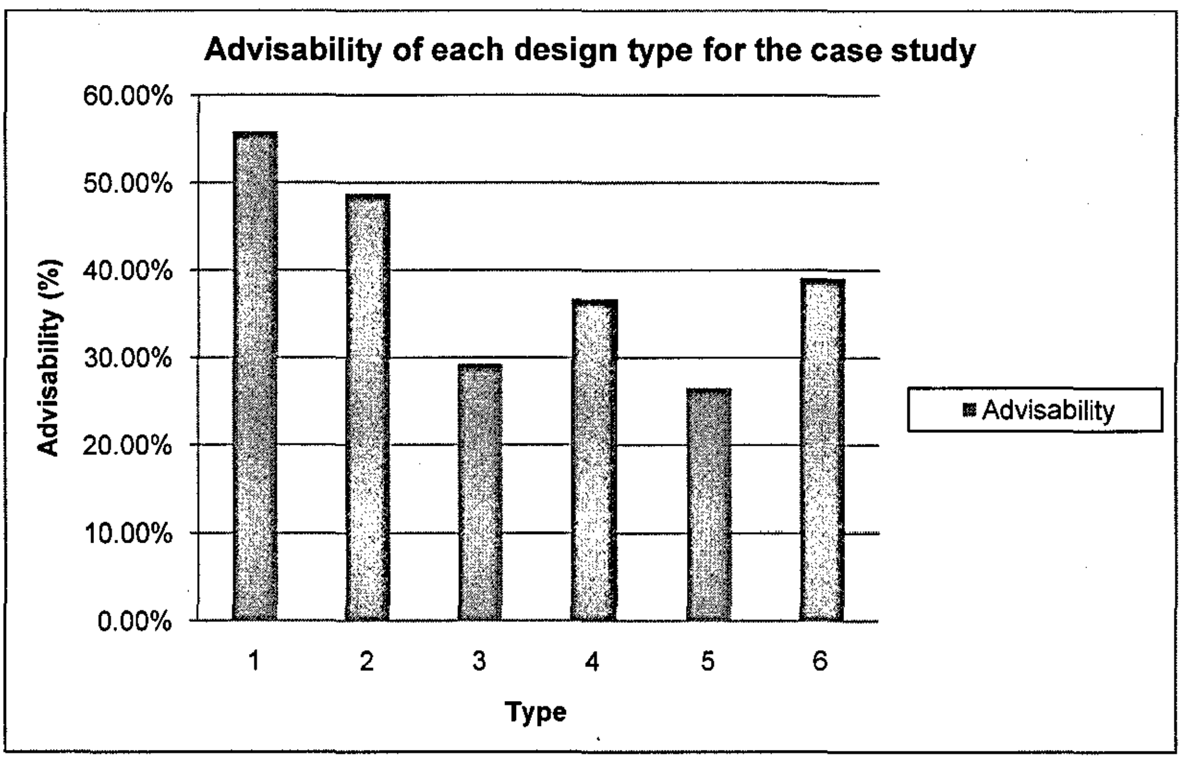


Figure 5.16 Final advisability of each type - an energy consumption and thermal comfort perspective

5.5. Discussion

In conclusion, the data needed for applying this procedure consists of the following categories:

- Architectural details: Obviously the more detailed the design specifications of a model, the more accurate the results obtained by that model. However, considering that this sort of study normally takes place in the very early stages of the design, having a full understanding of all architectural details seems very unlikely. In the exemplary case discussed in this chapter, all potentially applicable designs were categorised and simplified to their basic geometrical characteristics based on a well-established common method. Therefore, in the simulation stage, they could be treated as real-scale geometrical shapes made out of construction materials and put under outdoor weather conditions. That means that no internal layout or furniture or garden and water features or lifestyles could affect the results of the simulations.
- Constructional details: Unlike the previous category, most of the data needed in this category are normally known at the early stages (at least to the extent needed by these tools). This knowledge comes from either the standards or codes of practice as legislated by relevant local authorities or from the norms of the trade practiced by a specific design consultant. In the present example of the application of the method, part of the data mentioned to be derived from local standards and norms. Most of other data are based on the suggestions by common acceptable construction practices as described by references or simply the default values suggested by the simulation programmes.

- Weather data: Since the microclimate built by the building and its adjacent open space is the main area of concern in this study, accessing the local data in a microclimate scale is of ultimate importance here. However, this data is very rarely available in that scale and therefore, the closest weather conditions have to be treated as the most relevant. The weather data used in this example are the data on a normal year based on a 55 year record. This plus the local patterns of sun movement that is directly calculated by both TRNSYS and ENVI-Met as well as average thermal properties for the surrounding natural elements (like air and water vapour) as proposed by references will provide all the information needed for running the required simulations.

These data were processed through the integral procedure of indoor and outdoor simulation, as introduced in Chapter 4, and provide the information and the results needed to suggest a ranking of the different designs based on their indoor and outdoor thermal performance. Conclusions can be made based on the results of this exemplary case as follows:

- The example shows up to 35% saving on the annual energy bill of the building only as a result of the placement of the open space in a building. This is a strong proof for the necessity of further studies like this thesis on the correct application of the abilities of different architectural configurations of indoor and outdoor spaces in buildings.
- This energy saving is more obvious in the cooling demands of the building (45% compared to 20% saving in heating demands). This could be interpreted

as the higher importance of studies like this for regions with longer and warmer summers.

- Selecting the appropriate type of yard/building combination could also increase the number of thermally comfortable hours of the open space by more than 1000 hours (about 12% of a year) and, as mentioned before, this could prove to be a big advantage for families and cultures that value an outdoor living space.

6. Conclusions

This chapter presents the conclusions made as a result of the research presented into his thesis. The chapter is divided into three sections. In the first section the ways in which this thesis could be considered beneficial to the academic or professional communities are discussed. The second section reviews challenges that remain in the more general application of the findings of this study and the last section deals with what could be done in future studies to meet these challenges.

6.1 Contributions of the research

Contributions of the presented study could be discussed under three main categories: contributions to the knowledge of heat transfer and thermal comfort, contributions to improving existing simulation tools and contributions that are beneficial to the architects, designers and decision-makers of new urban developments.

6.1.1Contribution to the academia

- An analytical model of the thermal performance of a courtyard has been developed. Based on the radiosity approach, the model is capable of predicting the inner surface temperatures of a rectangular courtyard based on the air temperature in the courtyard and that in the rooms surrounding the courtyard. The conditions have been modeled at night, in the absence of solar radiation and have the potential of being further developed for the daytime, inclusive of the effect of solar radiation. Predictions from the model were used as part of an inter-model comparison for validating the output of ENVI-met, a simulation tool for predicting thermal behaviour in outdoor spaces.

6.1.2 Contributions to simulation practices

- The research provides further validation of ENVI-met, particularly in the area of predicting air temperatures. As mentioned before, currently there are not many outdoor thermal simulation tools available to researchers. One of the most promising programmes available for this purpose at the moment is ENVI-Met that was used in this research as one of the two main tools of simulation. It was also argued that ENVI-Met, being a newly introduced programme and still under development, needed to be approached cautiously. What was needed from ENVI-Met in this research included information on the air temperature and surface temperatures of the open spaces. To validate the results given by ENVI-Met on these two areas, a number of approaches were considered. These approaches, in addition to the analytical model introduced before, included the identification of real outdoor spaces and then modelling their thermal behaviour with ENVI-met, followed by comparing the predictions with measured data. In general, ENVI-Met proved to be suitable for the purpose of this research with some corrections and assumptions. The main correction, applied by cross-feeding the data between ENVI-Met and TRNSYS, was made to account for the problem encountered in ENVI-Met with regards to considering thermal capacity of the walls when calculating the wall energy balances. The assumption made was to minimise the effect of air speed by considering a very slow constant flow of air through all simulations. This measure was taken because of the inaccurate results predicted by ENVI-Met in comparison to the data measured on site during periods of significant and variable air speeds in the courtyard. These methods established the validity of the values predicted by ENVI-met for air temperature in the courtyard for low wind speeds. Nocturnal Surface temperatures of the courtyard walls, as calculated by ENVI-met, were also verified to be accurate.

However, daytime surface temperatures did not meet the standards of this research and were replaced by the results from TRNSYS.

- Introducing a technique for simulating indoor adjoining outdoor thermal environments based on the linking of two simulation programmes (TRNSYS and ENVI-met) is considered as another significant contribution of this research. Since there are presently no simulation programmes capable of considering indoor and outdoor heat transfer simultaneously, leading to interactions between the environments inside and around a building being ignored, an alternative approach had to be taken in order to achieve one of the main goals of the study, namely to assess the effects of the design of the outdoor spaces on the thermal environment inside the building. This alternative approach aimed at determining a suitable interaction between two programmes (TRNSYS and ENVI-Met), and proposed the nature of the data needed to be transferred from one to another. This was fully covered in Chapter 4 and was represented in a flowchart (Figure 4.22). Until a fully integrated simulation tool becomes available, this flowchart could be used in all similar situations where the interactions between indoor and outdoor thermal environments are investigated. It could also be altered for linking other pairs of programmes for specific needs of other studies.

6.1.3 Contributions to architectural and urban design practices

- This research established the effects of the location and positioning of an outdoor space that adjoins a building on indoor energy consumption and outdoor thermal comfort and that these effects are quantifiable by the technique presented in this thesis. An example of the application of the method, presented in Chapter 5, demonstrated that with all other conditions treated as equal, a change in the placement of the private outdoor space of a house, can make a substantial change to both the energy consumption of a household and the occupants' sensation of thermal comfort in the private outdoor spaces of their home. The results of the exemplary application of the method showed a cut of around 35% in the energy consumption of the building and a rise of more than 12% in the number of thermally comfortable hours achievable in the yard of a house, resulting solely from the positioning of the yard. These numbers will certainly be different in different cases, but confirm that such a study before finalising the layout of a design is definitely worthwhile.

- This thesis also presented a means for evaluating the placement of houses and their adjoining outdoor spaces within a housing development, in terms of energy consumption and outdoor thermal comfort. This could be considered the main contribution of this research because its achievement was one of the main aims of the research from the very beginning. The method introduced here, and later demonstrated through a sample study, could be used in any similar case, where a decision is to be made on the type of design selected for a new housing development. The means to evaluate the advisability of one design type over another from the point of view of energy consumption and outdoor thermal comfort, when combined with other social, economic and cultural factors, could be a very valuable tool in the hands of those who are in the process of making the decision for the final design adopted. This could concern all stakeholders in the process of the design, including policymakers, architectural and urban designers, investors, owners and most importantly occupiers and users.

- For example, it was established that for a climate like that of Isfahan, the two main factors to consider in the design of a house to make it more energy efficient are lower number of storeys and deeper plan layouts. Similarly, it was concluded that private open spaces adjacent to a house in this climate can be designed for offering a higher thermal comfort level if enclosed by the building on more sides and provide different areas with different level of solar radiation. Similar method can be applied for drawing such general results in other climatic situations.

6.2 Limitations of the research

In this section a number of limitations of the research are mentioned, together with suggestions for improvement. Some of these limitations were caused by the present lack of available knowledge in the field and some by the improvements that are yet to be made in the existing simulation programmes .

6.2.1 The outdoor thermal comfort index

Chapter 2 discussed in detail the process of selecting an outdoor thermal comfort index. As a result of this process, the index PET (physiological equivalent temperature) was selected. It was argued that PET offers, by far, the most accurate account of the human body's response to different environmental conditions and especially extreme conditions. The criticism made of PET is the same as that made of any other comfort index based solely on experiments and calculations rather than individuals' experiences and perceptions - that of ignoring the psychological aspects of man's interactions with his environment. The adaptive thermal comfort model offers an alternative to this genre of models but still fails to offer a definitive index, a metric that encompasses all factors affecting a person's thermal comfort in one comparable number. This means that, for example, the results offered for thermal comfort in the open spaces of the houses could be different if psychological adaptations of the users were to be taken into account. This, however, does not make the decision-making process, proposed in this research, invalid, since the part concerning outdoor thermal comfort is, in fact, the last step of the process and its results are not used in other parts. So, whenever an improved index for outdoor thermal comfort becomes available in the future, it could be easily incorporated into the procedure presented here.

6.2.2 Difficulty in considering air movement variations

The findings of this study are for the conditions of low or zero wind speed. Wind speed variations could thus have an effect on the results of this study. Local patterns of seasonal winds have always been an important factor in determining the final design of a house. The comparisons made between the results predicted by ENVI-Met against what was measured on site during the times of higher air speeds and turbulence, demonstrated a discrepancy in air temperature values. Based on this observation, the decision was made to continue thermal simulations by limiting the wind speed to very low values (the condition for which ENVI-Met results proved to be highly reliable). As discussed in chapter 3, this might have been caused by a variety of reasons (including reasons outside ENVI-Met's performance), but nevertheless it is not recommended to use the technique presented in situations where wind speeds in the surrounding area exceed 1m/s.

6.2.3 The weighting system between different influencing factors

To present the final ranking on the advisability of the types in Chapter 5, an equal weight was attributed to both the factors of energy efficiency and outdoor thermal comfort. In the same chapter it was discussed that this weighting regime was only an assumption and, in fact, it will be very difficult to give precise weights to these two virtually incomparable factors. This is because energy consumption is an idea dealing with economic and financial subjects (among others) and comparing such a subject with thermal comfort, which in essence contains a psychological and can differ from person to person and from society to society. The weights one can give to each of these two factors will depend very much on the economic and social status of the users and how much they are prepared to spend on their comfort when using the private outdoor spaces of their houses. It also depends on the culture and lifestyle of the household and the importance to them of having an outdoor living space. There are many other factors that could change the balance of this weighting scheme (e.g. air pollution, number of rainy hours and days, surrounding buildings etc.) and these have to be considered separately for each individual case.

6.3 Recommendations for further work

The in-depth consideration of the questions addressed by this research has opened new perspectives on the matter. Some of these perspectives focus on how such a study can be done with more accuracy in similar cases, and some deal with ways to exploit the results presented and the methods proposed in this thesis.

6.3.1 Development of an adaptive thermal comfort index

The importance of achieving a reliable and comprehensive outdoor thermal comfort index has been stated here more than once, but it is worth mentioning again that the existing knowledge on human physiological and behavioural response to the environment is at a level that seems to be a good base for the researchers in the area to start a serious effort in establishing an adaptive thermal comfort index. Although at the moment it is hard to predict if such an index would be inclusive of both indoor and outdoor thermal comfort senses of the users, the basic ideas of the adaptive comfort model seem to be universal and therefore applicable to both indoors and outdoors.

6.3.2 Day-time analytical model for wall temperatures

The analytical model for predicting surface temperatures of a courtyard that was one of the main contributions of this research could be developed into a comprehensive model by considering different times of the day and different sizes and shapes of courtyard. The simple night-time model presented here provides all the basics for the development of such a comprehensive model.

6.3.3 Further validation of ENVI-Met

From the point of view of this research the question of the validity of ENVI-Met under the conditions of high speed and high turbulence air movements remains unanswered. As mentioned before, this by no means should be taken as a verdict against ENVI-Met but rather as a "no verdict" in the case. The simplifications made for the reason of this research might be a crucial factor in delivering different predictions from direct observations and it is suggested that further validation is undertaken for the conditions of faster, more turbulent winds.

6.3.4 An integrated simulation programme

In this study, ENVI-Met and TRNSYS were linked via feeding the outputs of one programme to the other one and vice versa. It is recommended that this process is automated via suitable software approach. Alternatively, an integrated simulation tool could be developed, capable of considering continuous interaction of indoor and outdoor environments through walls and windows.

6.3.5 Developing and improving the decision-making tool

Finally, this thesis was aimed at providing help and guidance to those involved in a process of decision-making at the earliest stages of design procedure (sketch-design phase). This, in itself, could be made into a tool that enables its users to proceed faster in those early stages of the design instead of manually going through all the stages given this thesis. Such a tool will be improved even further if the proposed improvements on an outdoor thermal index and a reliable integrated simulation tool have been delivered. The development of such a comprehensive tool will be of high benefit to all stakeholders in the design process of a building or an urban development and in the long term will be beneficial to the users and occupiers of the buildings by offering more flexibility for them in using both indoor and outdoor spaces and also in reducing their dependence on fossil fuels for heating and cooling of their homes. The work presented in this thesis provides the basis for such future developments.

References

1. Aboulqasemi, L. (1995), *Garden* (in Persian), Iranian Cultural Heritage, Tehran

2. Al-Hemiddi, N.A. and Al-Saud, K. A. M. (2001), The Effect of a Ventilated Interior Courtyard on the Thermal Performance of a House in a Hot Arid Region, *Renewable Energy*, Volume 24, No. 3, pp. 581-595

3. Ali-Toudert, F (2005), *Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate*, Ph.D. Thesis, University of Freiburg, Freiburg, Germany.

4. Arnfield, A. J. (1990), Canyon geometry, the urban fabric and nocturnal cooling: a simulation approach. *Phys. Geography,* Volume 11 pp. 209–239

5. Asawa T., Hoyano A., Nakaohkubo K. (2004), Thermal design tool for outdoor space based on numerical simulation system using 3D-CAD. Proc. 21th Int. Conf. on PLEA, Eindhoven. Netherlands. Vol. 2: 1013-1018.

6. ASHRAE (2004), Standard 55 - Thermal Environmental Conditions for Human occupancy, ASHRAE Inc., Atlanta, USA.

7. Atkinson, G. A. (1950), Building in the Tropics, *RIBA Journal,* 57 (8), pp. 313-320

8. Atkinson, G. A. (1953), Building in warm climates, *Proceedings of BRAB Conference; Housing and Building in Hot-Humid and Hot-Dry Climates*, Report No. 5, Washington D.C.

9. Atkinson, M. (1962), *A consideration of vegetation, landscaping and micro-climatic conditions for building comfort*, M. Arch. Thesis, University of Melbourne

10. Bahadori, N. B. (1973), A feasibility study; solar heating in Iran, *Journal of Solar Energy*, 15, pp. 3-26

11. Bahadori, N. B. (1979), Natural cooling in hot arid regions, in *Solar Energy Application in Buildings*, Academic Press, New York

12. Baker, N. (1987) *Passive and Low Energy Building Design for Tropical Island Climates,* The Commonwealth Secretariat, London

13. Bansal, N. K. et al (1992), Effect of exterior colour on the thermal performance of buildings, *Building and Environment*, 27, pp. 31-37

14. Bourbia F., Awbi H.B. (2004), Building cluster and shading in urban canyon for hot-dry climate. Part 2: Shading simulations. Renewable Energy 29: 291-301

15. Bruse M. (1999), Die Auswirkungen kleinskaliger Umweltgestaltung auf das Mikroklima. Entwicklung des prognostischen numerischen Modells ENVI-met zur Simulation der Wind-, Temperatur-, und Feuchtverteilung in stadtischen Strukturen, Translation: Ali-Toudert, F. PhD Thesis, Univ. Bochum, Germany.

16. Bruse M. (2004), ENVI-met website. http://www.envi-met.com.

17. Buchberg, H. and Naruishi, J. (1967), On the importance of radiation exchange in the amelioration of thermal stress in enclosures, *Int. j. Biomet.* 11 (1), pp. 59- 78

18. Capeluto, I. G. and Shaviv, E. (2001), On the use of 'solar volume' for determining the urban fabric, *Solar Energy*, Volume 70, Issue 3, pp. 275-280

19. Cornell, P. H. (1957) Architecture in the Tropics. *Proc. Symp. On Design for tropical Living,* Durban

20. Danby, M. (1973) The design of buildings in hot-dry climates and the internal environment. *Build. Int.* 6 (1), pp. 55-76

21. Davies, A. D. M. and Davies, M. G. (1995) the adaptive model of thermal comfort; patterns of correlation, *Building Services Engineering Research and Technology*, 16, no. 1, pp. 51-53

22. De Dear R. J. (1994), Outdoor climatic influences on indoor thermal comfort requirements, *Thermal Comfort; Past, Present and Future,* Proceeding of a conference held at the Building Research Establishment, Garston, pp. 106-132

23. De Dear, R. J. and Brager G. S. (1998), Developing an adaptive model of thermal comfort and preference, *Field Studies of Thermal Comfort and Adaptation, ASHRAE Technical Data Bulletin,* 14, no. 1, pp. 7-49

24. Denyer, S. (1978) *African Traditional Architecture*, Heinman, London

25. Diba, K. (1996), *Typology of Iranian gardens* (in Persian), Fine Arts Faculty Publications, Tehran

26. Donham, D. (1960) The courtyard house as a temperature regulator, *The New Scientist*, 8, pp. 663-666

27. Ehlers, E. (1986) *Fundaments of a Geographic Demography*, Sahab geographic and cartographic institute, Tehran

28. Etzion, Y. (1989), The thermal behaviour of non-shaded closed courtyards in hot arid zones, *Architectural Science Review*, 33, pp. 79-83

29. Fathi, H. (1986), *Natural Energy in Vernacular Houses- Principles and Examples with Reference to Hot Arid Climates,* University Press, Chicago, 1986

30. Fisher, W. B. (1968), *The Cambridge History of Iran*, 1, The University Press, Cambridge

31. Food And Agriculture Organization Of The United Nations (2004), *SD Dimension,* www.fao.org

32. Givoni, B. (1998), *Climate Considerations in Building and Urban Design,* New York

33. Givoni, B. (1962) Influence of ceiling on thermal condition in dwelling houses in Beer-Sheva, *Building Research Station,* Technion, Research Paper 10

34. Givoni, B. (1976) *Man, climate and architecture,* Applied Science Publishers, London

35. Givoni, B. (1994) *Passive and Low Energy Cooling of Buildings*, Van Nostrand Reinhold, New York

36. Gooje, V (2003), Courtyard Performance; Geometry and Solar Influence, Proceedings of the Solar Conference, Austin, USA, 21 -26

37. Gooje, V. (2003) courtyard Performance; Geometry and Solar Influence, Proceedings of *the Solar conference*, American Energy Society and American Institute of Architects, pp. 783-788

38. Gotz, A. (1986) The Presentation of climatic data must be related to the design process, *Climate and Human Settlements Integrating Climate into Urban Planning and Building Design*, UNEP, Nairobi

39. Hariry M. and V. Millany (1985), *Climatic Classification of Iran,* Tehran University Press, Tehran

40. Heidarpour, A (2002), Experiments on the Environmental Effects of Traditional Residential Architecture (in Persian), The Scientific Magazine of Civil Engineering Department of Isfahan University of Technology, Vol. 2, No. 11, pp 17-28.

41. Heydari, S (2000), Thermal Comfort in Iranian Courtyard Housing, Ph.D. Thesis, University of Sheffield, Sheffield, UK.

42. Höppe, P (1999), The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, International Journal of Biometeorology, Vol. 43, No. 3, pp 71-75.

43. Information Technology Associates, (2004), *Geographic Reference,* www.theodora.com

44. International Energy Agency, (2004) *Statlist 2003,* www.iea.org

45. Ministry of Housing and Development (1993), *Iranian National Building Code,* , Tehran

46. Kassmai, M. (1992) *Climatic Classification f Iran,* Building and Housing Research Centre, Tehran

47. Kim, S. Y. (2002) *Optimising Courtyard Housing Design for Solar Radiation Within Dense Urban Environments,* Ph.D. Thesis, University of Sheffield, Sheffield

48. Koenigsberger, O. H. et al (1973), *Manual of Tropical Housing and Building,* Longman, London

49. Konya, A. (1980) *Design Primer for Hot Climates,* Architectural Press, London

50. Lippsmeier, G. (1969) *Building in the Tropics,* Verlag George D. W. Callwey, Munchen

51. Malekzadeh, M. (2002), Internal migration in growing cities (in Persian), *Arg,* Volume 14, Issue 2, pp. 27-33, Tehran

52. Malekzadeh, M. and Loveday D. L. L. (2008), *Towards an integrated simulation of indoor and outdoor building spaces,* proceeding of Windsor Conference 2006, London Metropolitan University, London

53. Martinot, E. (2000) *Promoting Energy Efficiency and renewable Energy,* Global Environment Facility, Seattle

54. Matzerakis, A. et al (1999), Applications of a universal thermal index: Physiological Equivalent Temperature International Journal of Biometeorology, Vol. 43, No. 2, pp 76–84.

55. Memarian, G. (1998), *Persian House Typology,* University of Manchester, Ph.D. thesis

56. Merghani, A (2001), Thermal comfort and spatial variability in courtyard houses in hot dry climates, Ph.D. Thesis, University of Cambridge, Cambridge, UK.

57. Merghani, A. (2001), *Thermal Comfort and Spatial Variability; A Study of Traditional Courtyard Houses in the Hot Dry Climate of Khartoum, Sudan,* Ph.D. Thesis, University of Cambridge, Cambridge

58. Mills, G. A. (1997), Objective Prediction of Severe Thunderstorm Environments: Preliminary Results Linking a Decision Tree with an Operational Regional NWP Model, *American Meteorological society Journal*, Volume 13, Issue 14, pp. 1078-1092

59. Mohsen M. A. (1978), *The Thermal Performance Courtyard Houses,* Ph.D. Thesis, University of Edinburgh, Edinburgh

60. Mohsen, M. A. (1979), Solar radiation and courtyard house forms; A mathematical model, *Building and Environment*, Volume 14, Issue 2, pp. 89-106

61. Mohsen, M. A. (1979 b), Solar radiation and courtyard house forms; Application of the model, *Building and Environment*, Volume 14, Issue 3, pp. 185-201

62. Oklahoma State University (2005), *Department of Geography Map Server,* www4.geog.okstate.edu

63. Olgyay, V. (1967), Bioclimatic orientation method for buildings, *Int. J. Biomet.* 11 (2), pp. 163- 174

64. Olgyay, V. (1963), *Design With Climate - Bioclimatic Approach to Architectural Regionalism,* Princeton University Press, Princeton

65. Pope, A. (1982), *Persian Architecture*, Charles E Tuttle Co, London

66. Rapaport, A. (1969), *House Form and Culture,* Prentice-Hall, New Jersey

67. Ratti, C and others (2003), Building Form and Environmental Performance; Archetypes, Analysis and an Arid Climate, Energy and Buildings, Vol. 35, No. 1, pp 49-59.

68. Reynolds, J. S. (2001), Courtyard Cooling; Proportion versus Proaction, *Forum*, No. Conf26, pp. 625-630

69. Reynolds, J. S. (2002), *Courtyards; Aesthetic, Social and Thermal Delight,* John Wiley, New York

70. Richard S. J. (1957) Climatic control by building design. *Proc. Symp. Design for Tropical Living,* Durban

71. Saini, B. S. (1973) *Building Environment; An Illustrated Analysis of Problems in Hot Dry Lands,* Angus and Robertson, Sydney

72. Saini, B. S. (1962) Housing in the hot arid tropics, *Architectural Science Review,* 5 (1), pp. 3-12

73. Saremi, A. (1998) The new Housing Design, *Art and Architecture,* 12, pp. 23-29, Tehran

74. Skeat, W. (2007), *The concise Dictionary of English etymology,* Wordsworth editions Ltd, London

75. Solar Energy Laboratory (2006), http://sel.me.wisc.edu/publications/publ.html, SEL Publications, The Website of the University of Wisconsin, Madison, USA.

76. Tavassoli, M (1983), *City Planning in the Hot, Dry Climate of Iran.* In: Golany, G (ed), Design for Arid Regions, Van Nostrand Reinhold Company Inc., New York, USA.

77. Tavassoli, M. (1999), *The Alphabets of the Vernacular Houses; Yazd,* Tehran University, Tehran

78. The Islamic Legislative Assembly (2000), *The Third Five Year Plan for the Economical, Social and Cultural Development of the Islamic Republic of Iran,* Majles Publications, Tehran

79. Trewartha, G. T. (1968), *An Introduction to Climate,* McGraw-Hill, New York

80. Solar Energy Laboratory (2008), Volume 16: Standard Component Library Overview, TRNSYS manual, Wisconsin University

81. Tropical Advisory Service (1966), *Climatic Design,* Report prepared for the Ministry of Public Building and Works, London, UK.

82. U. N. (1971), Department of Economic and Social Affairs, Design of low-cost housing and community facilities, *Climate and House Design,* 1, U. N. Publication, New York

83. U.S. Environmental Protection Agency (2002), Time for a change; a guide to energy-efficient cooling, *Energy Star,* Washington D.C.

84. Undersecretary of Energy Affairs (2003), *Energy Balance sheet 2003,* The Publications of the Ministry of Power, Tehran

85. US department of Energy, (2008), www.energy.gov, Washington

86. Van Straaten, J. F. and Van Deventer, E. N. (1964) The functional aspects of building design in warm climates with particular reference to thermal ventilation considerations. *Int. J. Biomet.* 8 (2), pp. 155-163

87. Wilson, A. T. (1930), *A Bibliography of Persia*, Oxford University, Oxford

88. World Atlas (2004), *Countries,* www.worldatlas.com

89. World Sites Atlas (2004), *Maps of Countries and Territories,* www.sitesatlas.com

90. Zandjani, H. (1998) Iran through history, *Abadi,* 27-28, pp. 15-22, Tehran

Appendix A

Paper presented to Windsor International Conference 2008, "Air-Conditioning & the Low Carbon Cooling Challenge":

Towards the Integrated Thermal Simulation of Indoor and Outdoor Building Spaces

M. Malekzadeh and D. L. Loveday

Department of Civil and Building Engineering,

Loughborough University, Loughborough, LE11 3TU, UK

Abstract

In this paper, a standard "Indoor" simulation programme (TRNSYS) and an "outdoor" simulation programme (ENVI-met) have been linked in order to assess the energy performance of some typical Iranian housing designs as influenced by their adjacent outdoor space conditions. The paper reports on the challenges encountered in establishing the interaction between the two programmes, together with approaches that could be used to solve some of the problems. Following a description of the approach, results are presented of the heating and cooling energy demands for a range of house designs, in both singular and urban multiple configurations. Thermal conditions of the adjacent outdoor space (yard or courtyard) are also predicted and their effect on outdoor thermal comfort is assessed. The work provides the basis for the development of a simulation tool that addresses the thermal interaction between indoor and adjacent outdoor spaces in an integrated manner.

Keywords: TRNSYS, ENVI-met, courtyard, Iran, outdoor thermal comfort

1. Introduction

In many cultures the private outdoor space adjacent to a building fulfils an important function. In the UK, for example, the classic concept of the "English country garden" conveys a cultural gravitas that is comparable to that of the "central courtyard" of Iranian houses. Central courtyard buildings (Figure 1) were the main building type for Iranian houses for many centuries, but despite their cultural, historical and artistic values, the energy efficiency and thermal comfort of central courtyard buildings have been subject to debate in recent decades. For many years, most researchers have suggested deep forms for the buildings in a hot-arid climate (Olgyay 1963, Ratti 2003) - forms as close as possible to a cube with the least amount of wall and roof area exposed to the harsh weather outside.

Presently, this idea of box-like housing is the most frequently-practiced concept in most Iranian cities and in many rural areas. However, now and after practising this research-based idea for a few decades, doubts have arisen about the energy performance of these box-like buildings, in particular with regard to the level of thermal comfort they offer both indoors and in their enclosed open spaces. Some surveys (Merghani 2001) suggest much less need for heating and especially cooling

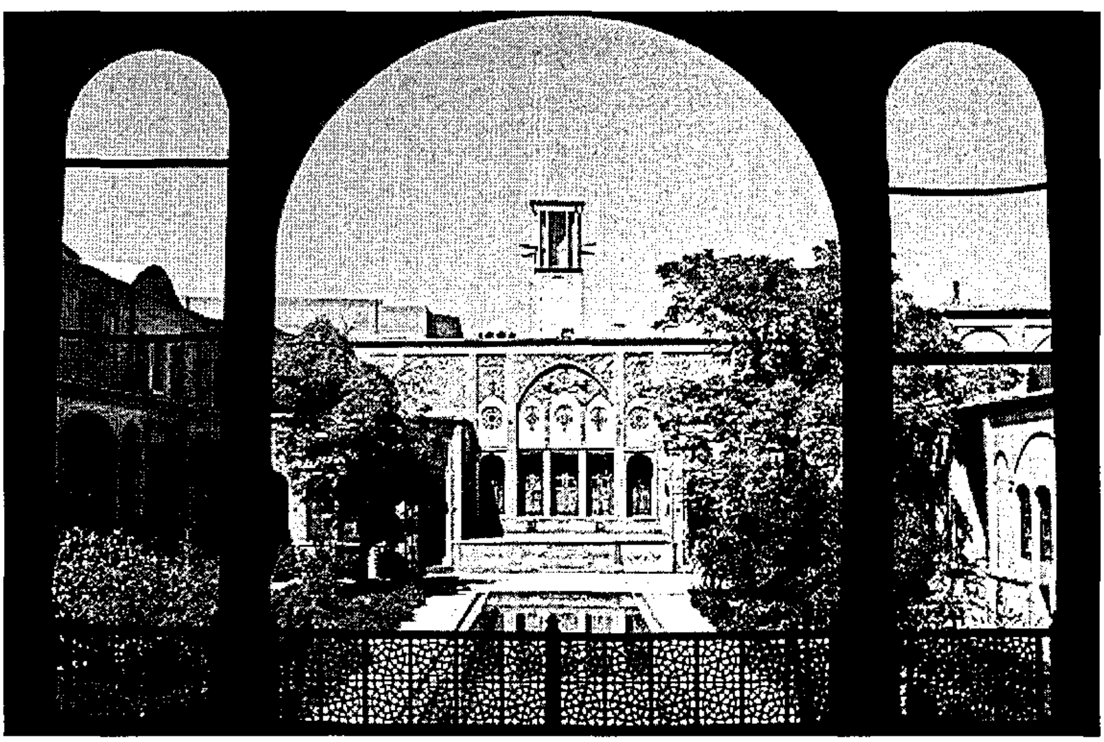


Figure 1: Borujerdis' House, Kashan, Isfahan Province, Iran

in some old central courtyard buildings compared to the more recent types where front or rear yards are provided. This suggestion is supported by public opinion surveys, indicating that the historical central courtyard building type is assumed to be thermally more comfortable, particularly in summer time (Heydari 2000). It has also been argued that this perceived comfort advantage of the historical type of housing could be a result of many different factors (Gooje 2003). Some of these factors could include:

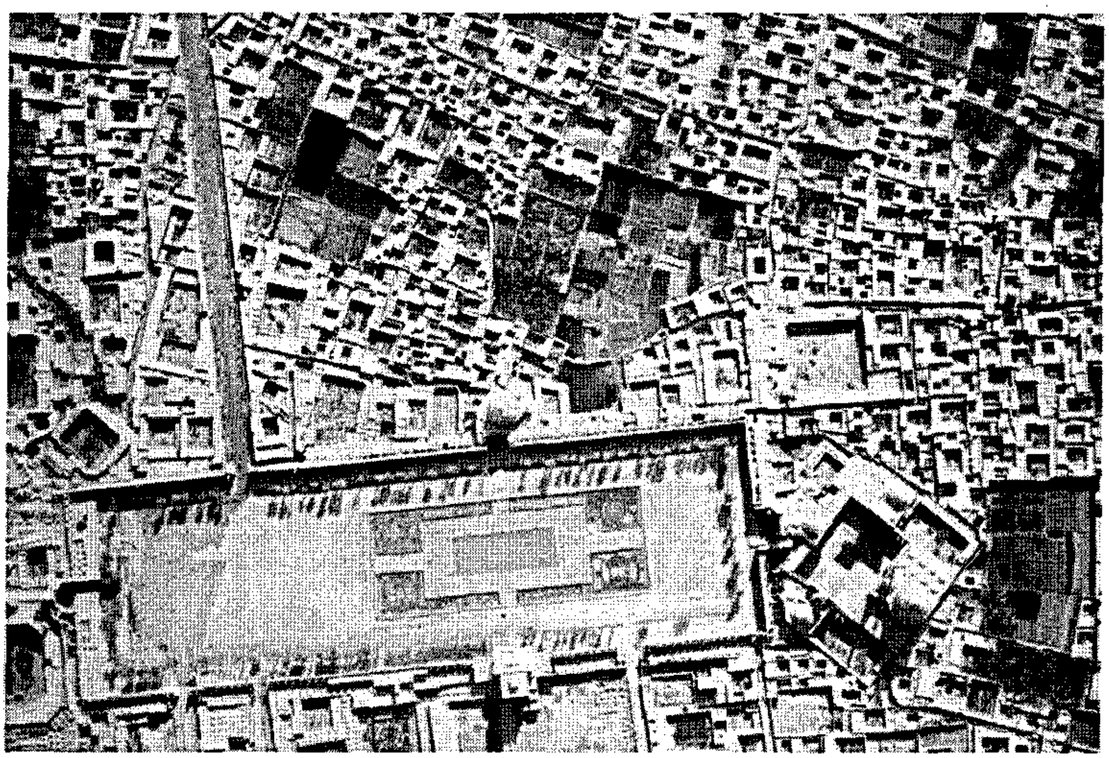


Figure 2. A combination of courtyards of different sizes - Isfahan, Iran (Tavassoli 1983)

- height of indoor spaces allowing for replacement of the rising heated air with fresh and cool air;

- high walls adding to the shaded area of the open space;

- heavy materials used in the construction of the walls, providing high thermal capacity, insulation and heat exchange lag time;

- additional architectural intricacies serving a secondary role as shading devices;

- bigger size of the traditional houses offering some flexibility in using different parts of the house in different weather situations;

- the impression that central courtyards are simply more usable and therefore enjoyable;

- the extent to which foliage and water features are used in historical houses, which could contribute to evaporative cooling as well as providing some extra shading;

- the compact urban texture of traditional neighbourhoods (Figure 2) leaving a minimum percentage of the wall area exposed to outside conditions.

A strong argument that could be made here is that applying these additional features might improve the comfort sense in any building type. Therefore, it is impossible to conclude whether the suggested enhanced perception of comfort in the vernacular housing type is in any way an effect of the placement of the courtyard in the centre of the building.

In order to develop a better understanding of the impact of the placement of the adjacent open space (such as a courtyard) on the performance of the whole building, research has been carried out at Loughborough University towards developing a comparison method between different house/yard combination styles in the design layout of a residential building. The results of this research can contribute to the process of decision-making when selecting the general style of future housing developments based on the local weather situation.

2. Positioning of Outdoor Space in House Design – An Energy Efficiency and Thermal Comfort Perspective

As discussed in the introduction, a direct comparison between the different house design types is impossible, unless we strip the different compared types from their additional features (or simplify them) until we are left with the position of the open space as the only difference between the types. Computer simulation offers the most convenient way to perform this comparison.

Following an extended review of the programmes available for simulating thermal performance of buildings and because of the current lack of simulation software capable of dealing with both the building and its adjacent open space, two programmes were selected to simulate separately the conditions inside the building and in the adjacent open space.

There are a good variety of well-established programmes for simulating and predicting the thermal conditions inside a closed building. Among them TRNSYS, being one of the most widely validated programmes (SEL 2008) and offering a user-friendly environment and an efficient technical support, was chosen to study the indoor thermal condition of the buildings.

For the outdoors aspect of the simulations, on the other hand, there are limited choices available. ENVI-met is a relatively new programme offering a modelling solution to predict the interactions between surfaces and the air of the outdoor environment. In addition to the validation results available (Ali-Toudert 2005), further analytical modelling and direct measurements were carried out during this research to determine whether ENVI-met could be used as a functional tool, suitable for the purpose of modelling the outdoor thermal environment in spaces adjacent to buildings.

3. Case Study

A hypothetical plot of land in Isfahan, central Iran, was chosen, assumed to be in the process of general planning for a new residential development project. The aim of the research was to develop a design/decision method that should be capable of recommending the type of house/yard combination that offers less energy consumption by the building and a greater number of hours of thermal comfort both inside the building and in the private open space adjacent to it. The assumed plot of land was an urban block with given dimensions, bordered by local access ways from all sides and including 8 equally-sized and shaped pieces of land in two rows of 4.

Different commonly-used house/yard combinations applicable to this case were studied, categorized and simplified based on a method suggested by research at the

University of Cambridge (Ratti 2003). As a result, 6 different types of housing designs were set up. Each of these types is a simplified representation of one of the house/yard configurations studied here (Figures 3 and 4)

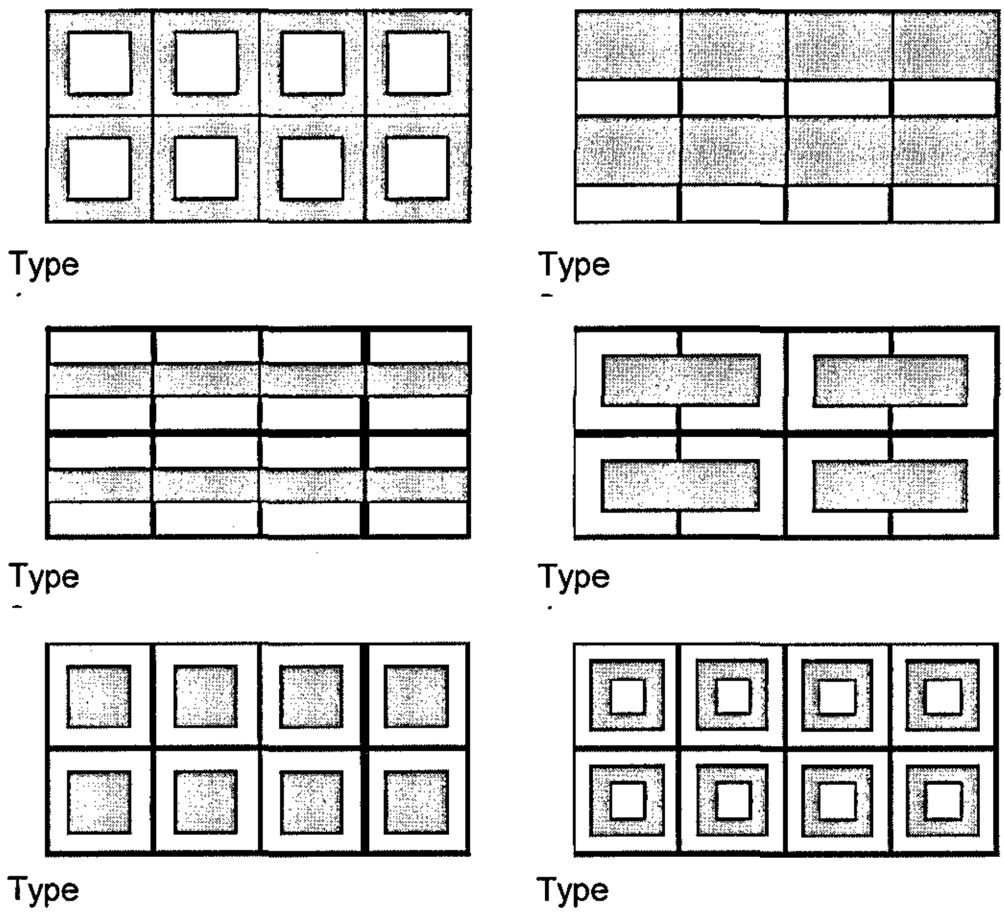


Figure 3. Six simplified house/yard combination types

All the types occupy equal areas of land, as well as having equal areas under their roofs. The total building volume, the height of the internal spaces, the materials used in the walls and their thickness, and the percentage of the window area in each direction are equal in all cases. There are no added active or passive cooling or heating systems in any of the building types, and every effort has been made to keep all the specifications of the types similar to each other, in order to restrict the differences between them to being only their design layout.

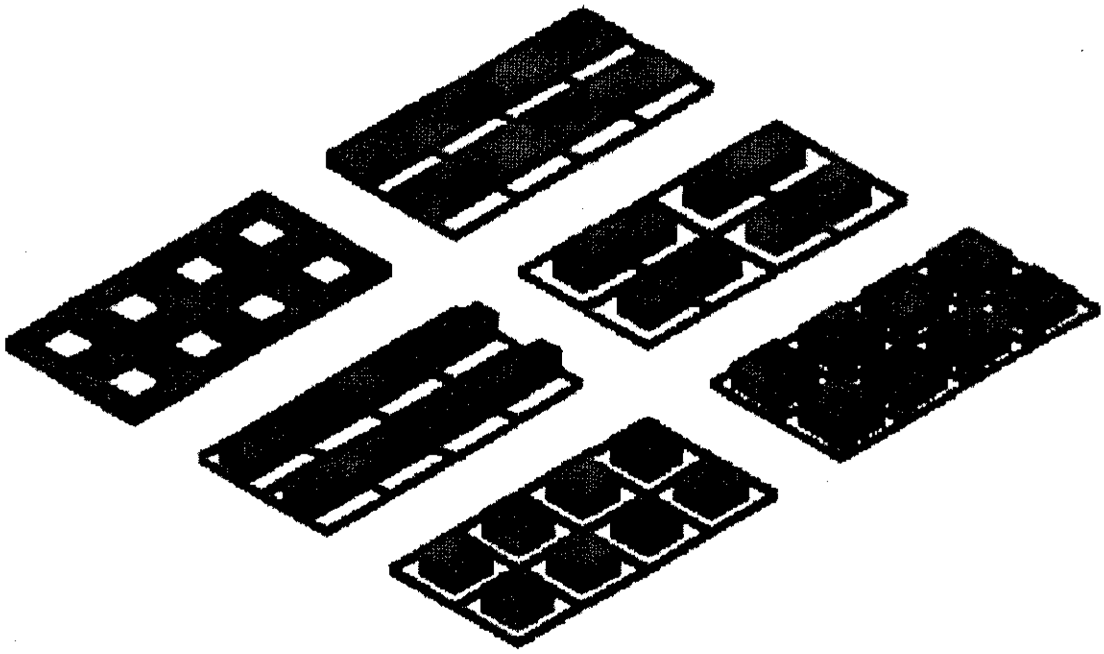


Figure 4. A 3D view of the six simplified house/yard combination types

4. Procedure

The procedure adopted was to focus on air temperature as the defining factor between the types as a metric of their energy performance as well as their state of thermal comfort. All other environmental factors such as humidity, air speed, etc. were assumed to be identical and, therefore, bearing an equal impact on all types.

4.1. Air Temperature in the Courtyard

Part of the data needed by TRNSYS for determining the air temperature inside a building (t_i) is the air temperature outside the building (t_o). Surveys show that the air temperature measured inside an enclosed open space (such as a courtyard) is, in most cases, different from the air temperature measured at the nearest weather station (Heydari 2000).

Figure 5 presents the plan view of a central courtyard house in Isfahan, Iran and Figure 6 shows the average temperature values measured at the middle point of the courtyard by a research group from the University of Isfahan (Heydarpour 2002) for a

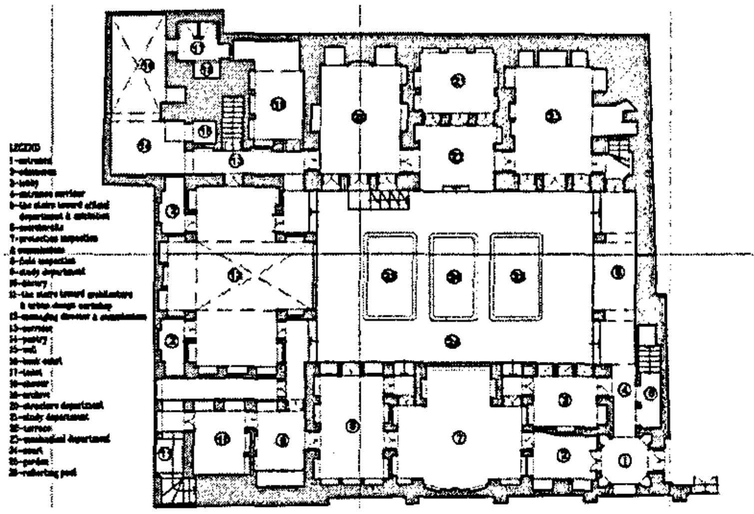


Figure 5. Polsheer House - Isfahan, Iran (Heydarpour 2002)

period of 24 hours, in comparison with the general outdoor air temperatures from the meteorological data for the same day. Observed temperatures in the courtyard show different values from the ones recorded at the nearest weather station (about 2.5 km away).

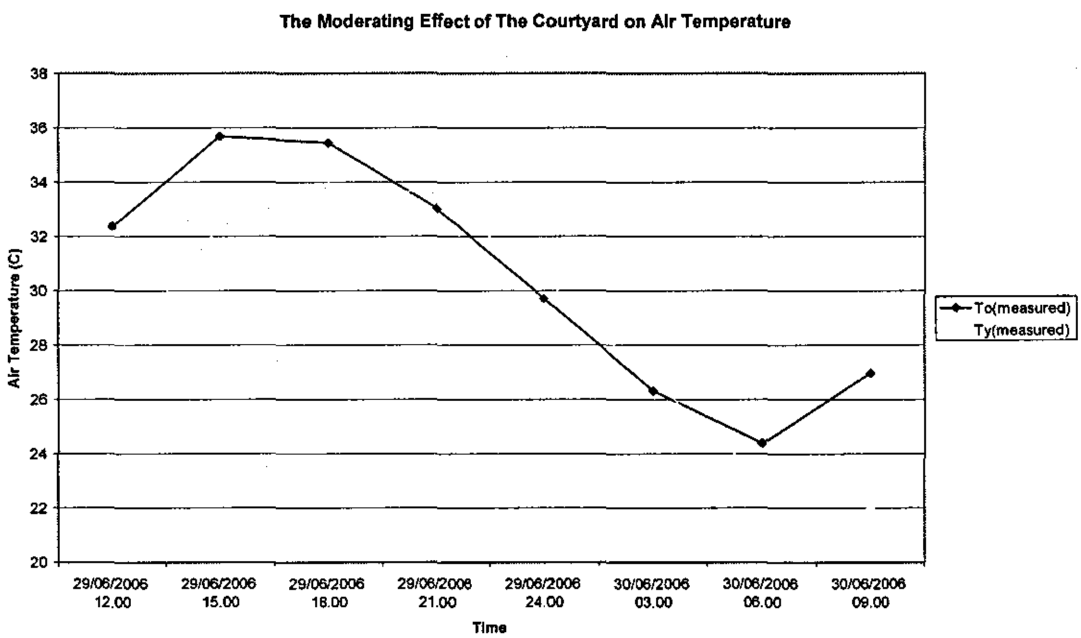


Figure 6. Air temperature inside and outside the courtyard

In this study, t_y represents the temperature inside the adjacent outdoor space (courtyard or yard), while t_o (outdoor air temperature) is the air temperature recorded at the weather station, which has been assumed to apply to all other surfaces of the building, including the roof.

4.2. Courtyard Air and Surface Temperatures Found by ENVI-met

To acquire a full set of hourly t_y values for the courtyard of each of the assumed house types of section 3, the ENVI-met programme was run using the hourly data from the weather file, assuming that the surface temperature (t_s) of all courtyard inner walls at the initiation point of the simulation is equal to t_o. To account for this assumption, the same data were processed on 2 consecutive days and the results of the second day were selected as the one represented in the research.

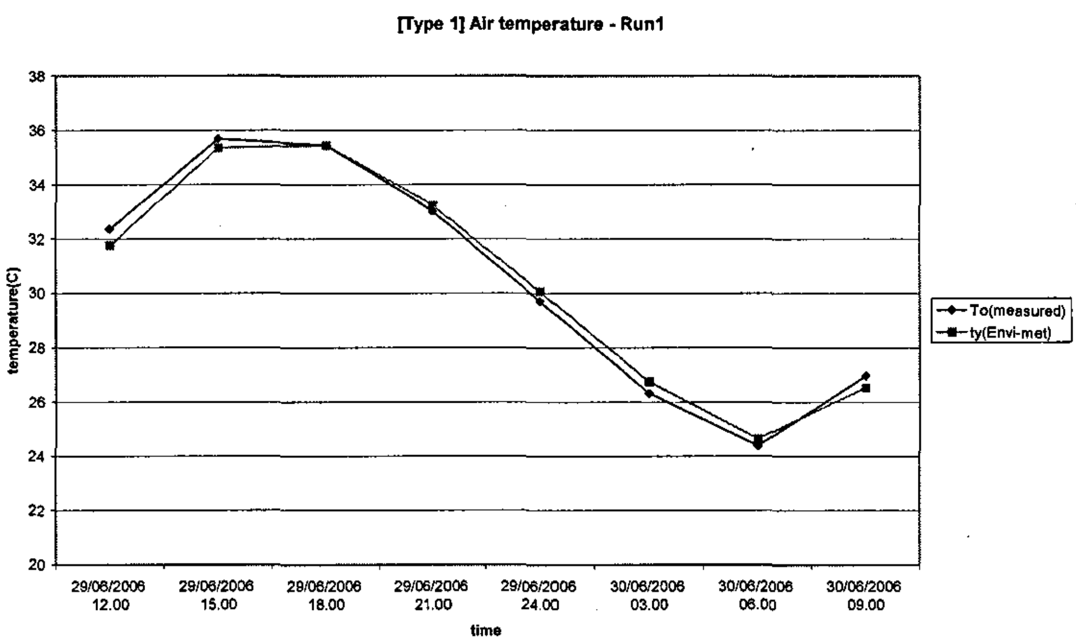


Figure 7. Air temperature in the courtyard before correcting for the effect of heat storage

Figure 7 shows the average air temperature of the courtyard for Type 1 (the central courtyard house in Figure 3) based on the temperatures predicted by ENVI-met at a height of 1 m above the ground for a 1 metre by 1 metre grid across the courtyard during a hot summer day in the city of Isfahan, Iran.

Comparing this set of temperature values (t_y) with the general outdoor temperature (T_o), shows some difference between the two, but this difference is far too small to confirm (among other studies) the results from direct measurements in Isfahan (Figure 6) of the moderating effect of the courtyards in both day and night. Moreover, the air temperature was found to be almost uniform in the courtyard air volume with insignificant warming up of air close to irradiated surfaces. This disagrees with field study results (e.g. Heydarpour 2002) and the results obtained from a similar experiment conducted in a university courtyard type building in Loughborough that both show higher air temperatures near the irradiated walls and an average air temperature in the courtyard that differs from the outdoor air temperature. This can be partly attributable to neglecting the heat storage property of the walls by ENVI-met. This problem, however, could be solved through TRNSYS in the next section.

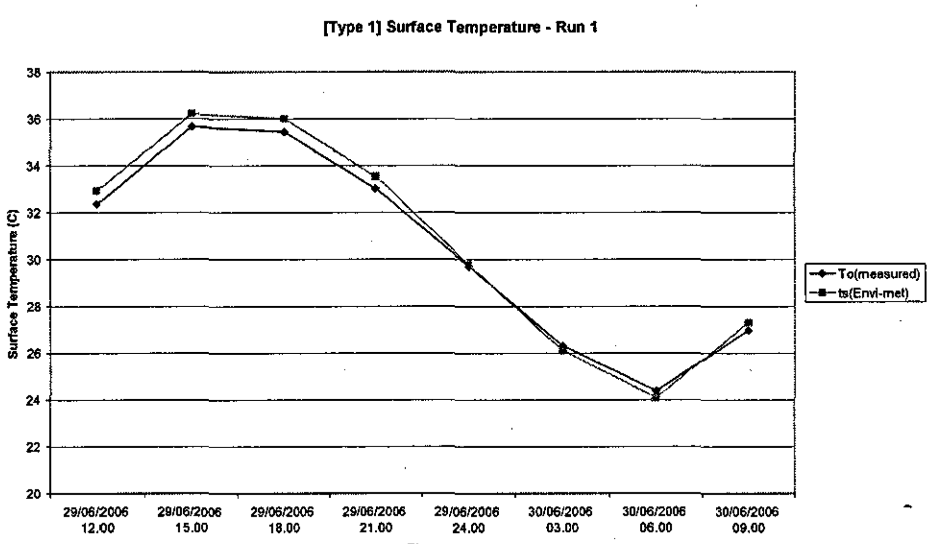


Figure 8. Average surface temperature of the south facing wall by ENVI-met

Figure 8 presents the average surface temperature (t_s) for a south-facing wall in the same simulation by ENVI-met. The surface temperature curve shows a very close adherence to the changes of the air temperature and does not comply with the results obtained from the measurements that demonstrate a time difference between the rise and fall of the two diagrams. Once more, this could be attributed to ignoring the heat storage in the simulation.

4.3. Indoor Air Temperature and Corrected Surface Temperature by TRNSYS

At this stage, a TRNSYS simulation could be run, using the air temperature recorded at the nearest weather station in addition to the new air temperature in the courtyard (predicted by ENVI-met). In order to supply the two different sets of surrounding air temperatures to the simulation, the courtyard was treated as an adjacent room with a changing predefined set of air temperatures, and then the heating effect of solar irradiation on different walls was calculated and added. This simulation predicts the average air temperature inside the building (t_i) together with a new temperature for the outer surface of the courtyard wall (t_{2s}). As presented in Figure 10, this new set of surface temperatures show a noticeable difference from the ones derived from ENVI-met earlier and signifies the delay time caused by the heat storage in walls.

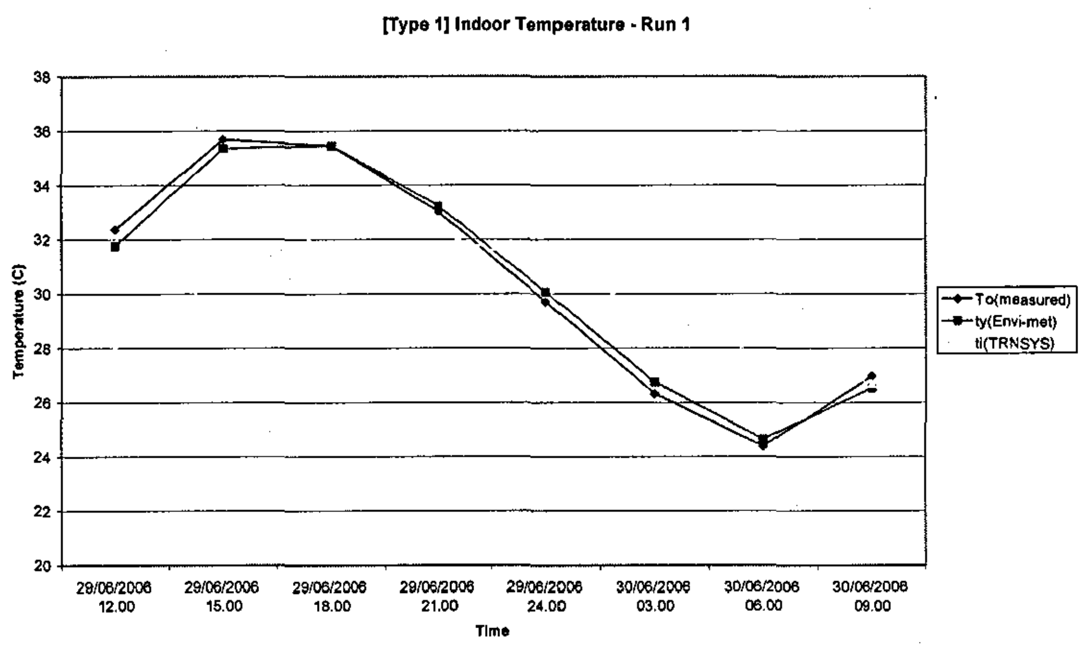


Figure 9. Indoor air temperature as predicted by TRNSYS

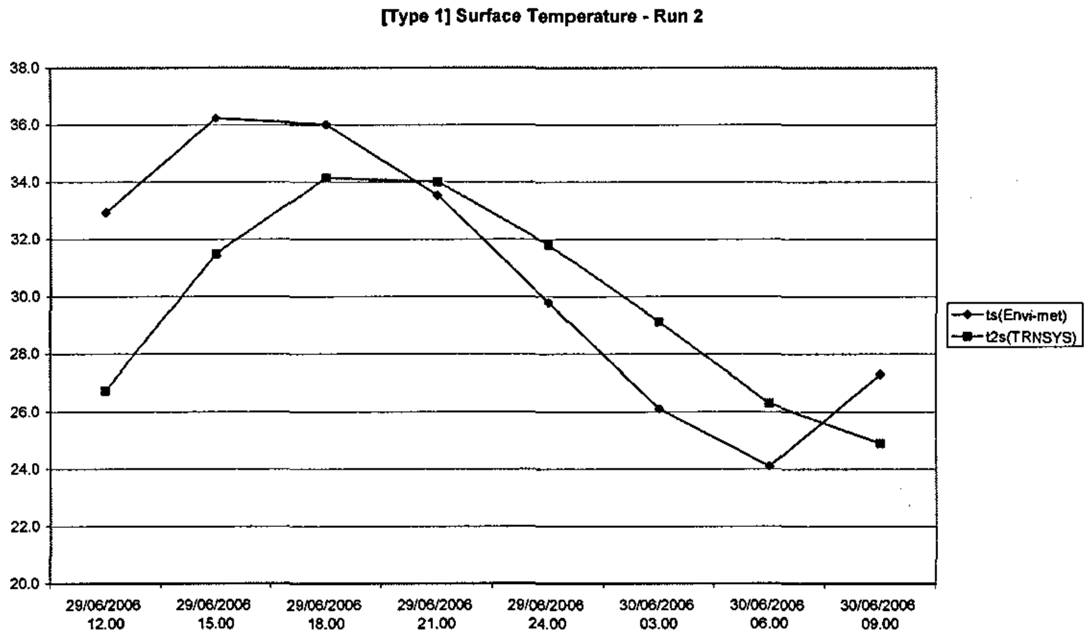


Figure 10. Surface temperature as predicted by TRNSYS

4.4. Corrected Courtyard Air Temperature by Iterations Between ENVI-met and TRNSYS

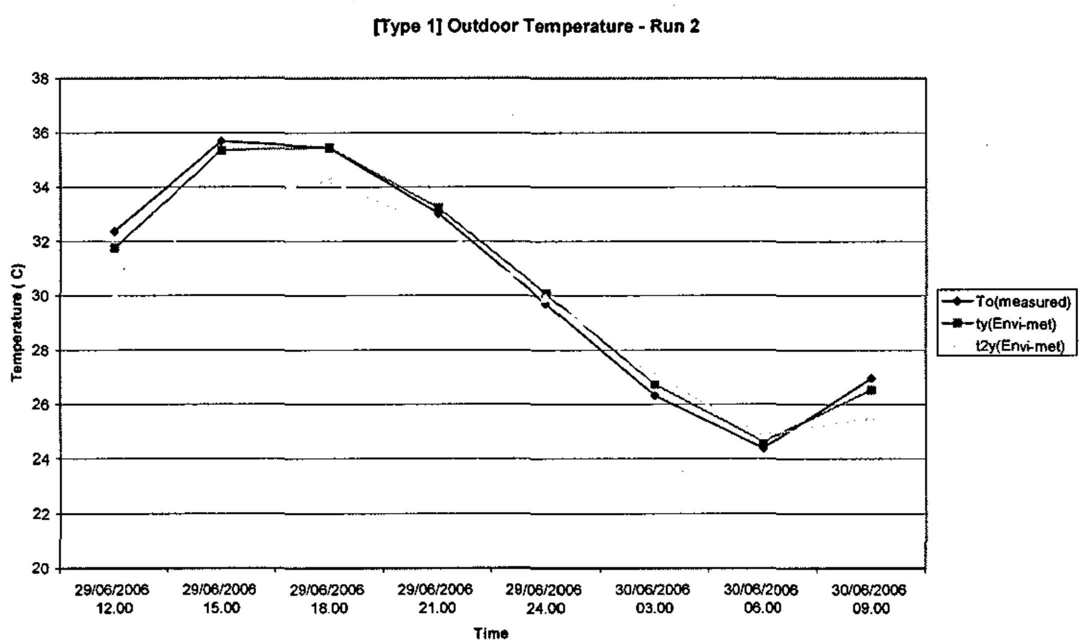


Figure 11. Air temperature in the courtyard after considering the effect of heat storage

It is observed (Figure 11) that running ENVI-met once again, but this time using the corrected surface temperatures, could result in new values for the air temperature in the open space (t_{2y}).

This suggests the need for a set of iterations between the two programmes in order to obtain the final values for indoor and outdoor air temperature as well as the surface temperature of the walls facing the courtyard. These iterations were repeated until the difference between the last two successive approximations of t_i achieved an acceptable degree of accuracy for this study (0.5°C). Figure 12 presents the final results for T_i on the selected day of the year for a single central courtyard house. These results could be used in calculating the heating and cooling loads of the building for that specific day.

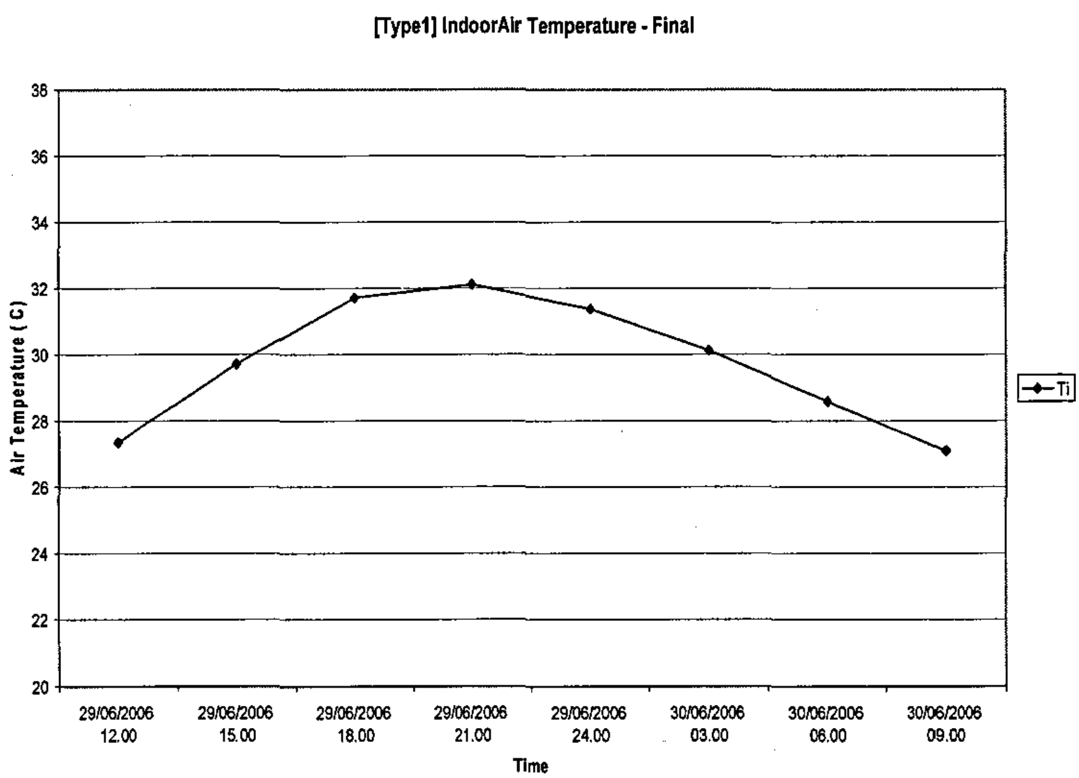


Figure 2. Final indoor temperature after iterations

4.5. Calculating Heating and Cooling Loads by TRNSYS

So far in these simulations, no added heating or cooling has been considered, but in order to achieve the minimum thermal comfort inside the building, a set temperature range of 20 to 26°C is needed to be maintained by some cooling and/or heating device (ASHRAE 2004). This will result in a new set of values for indoor air temperature in

the room, called T_r. Repeating the procedure described above for other months of the year, hourly T_i and T_r values for a whole year of standard weather data can be calculated (a sample of which has been presented in Figures 13 and 14).

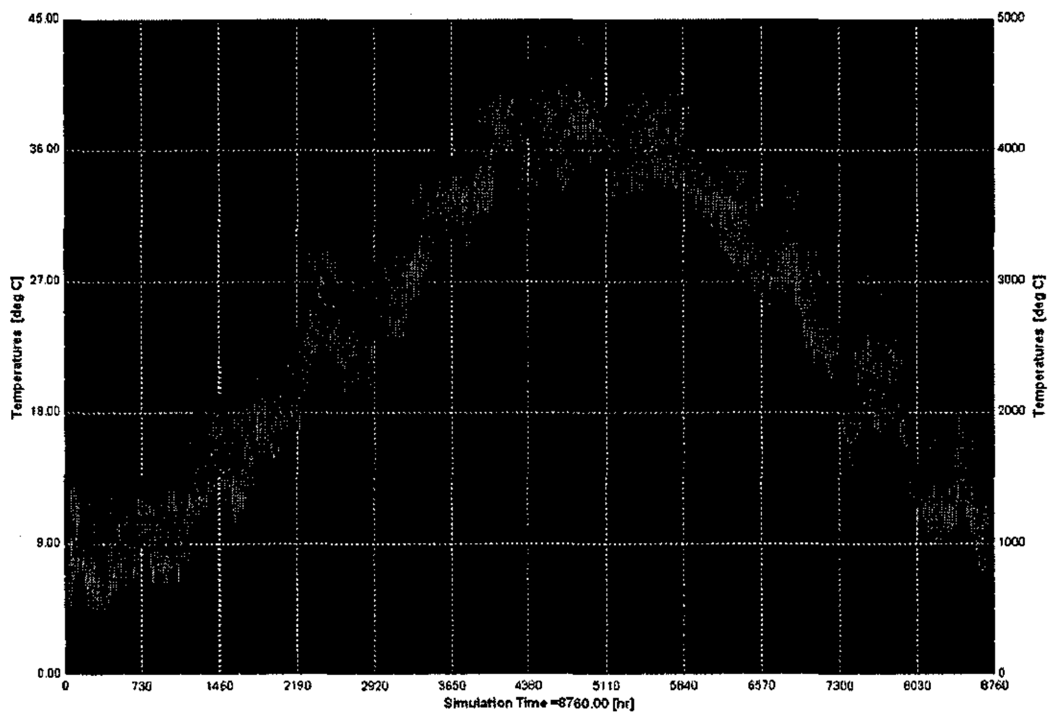


Figure 3. hourly indoor temperature before adding heating or cooling (Types 3,4,5)

These two sets of temperatures could be used to predict the heating and cooling loads of this building type. Figures 15 and 16 show the comparative diagram of yearly heating and cooling loads for all six types of the buildings depicted in Figure 3. This could be used as one of the main decisive factors for choosing the type that offers the best thermal performance. In this case, house designs Type 2 and Type 5 offer the minimum annual heating and cooling loads, respectively.

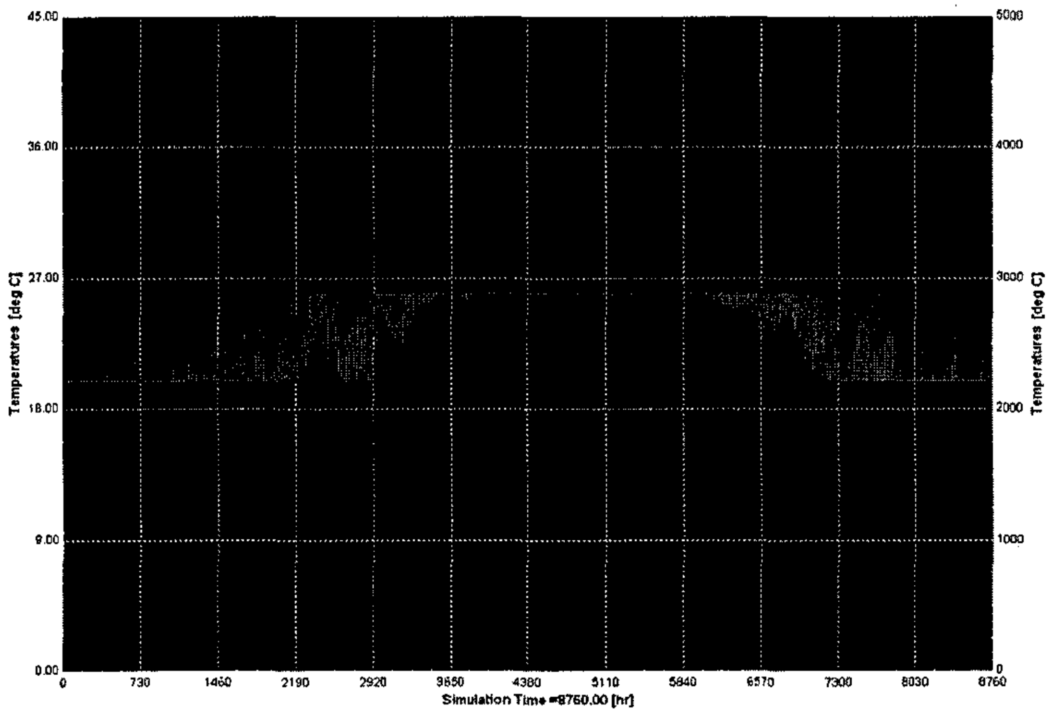


Figure 4. Final indoor air temperature for a normal year (Types 3,4,5)

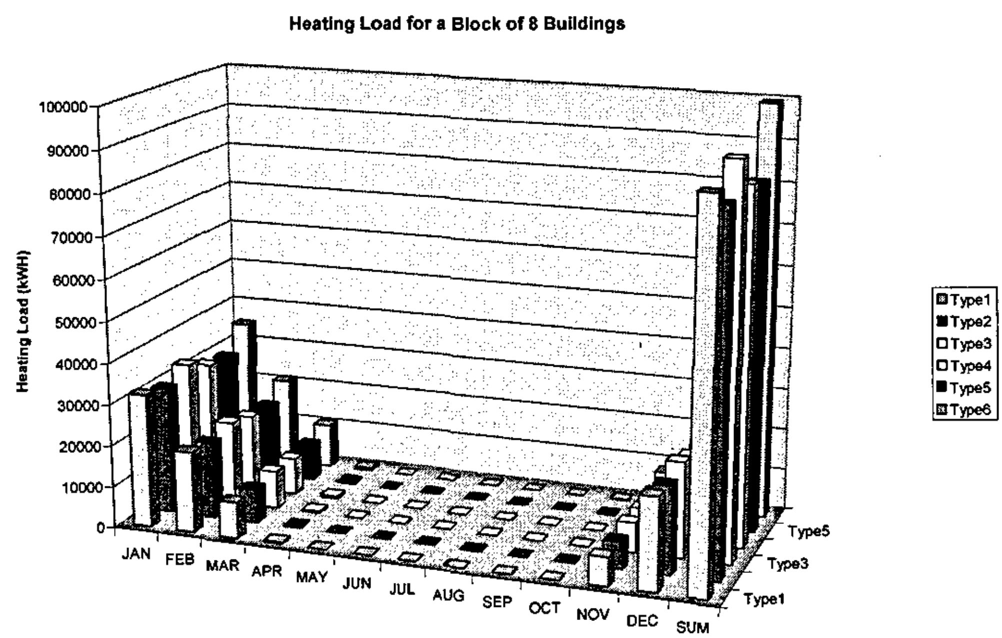


Figure 5. Monthly and yearly heating loads for the urban block (all types)

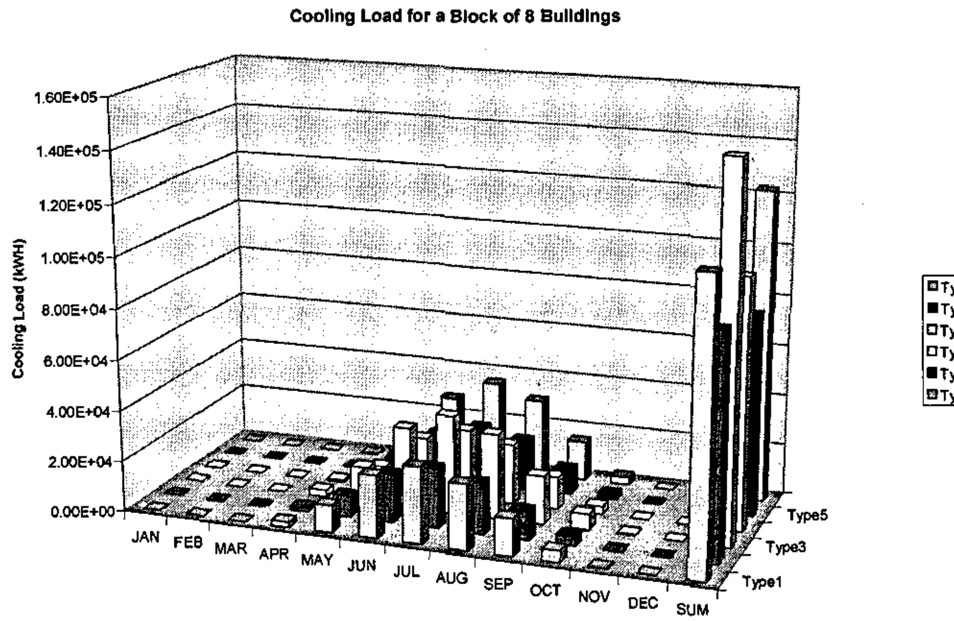


Figure 6. Monthly and yearly cooling loads for the urban block (all types)

These diagrams also show the significant impact of the design layout on energy demands of the buildings with similar specifications. It can also be argued that this difference is more critical in the cooling loads of the buildings and therefore making the choice of an appropriate design, more important in places with longer hot seasons.

4.6. Final Values for Courtyard Air and Surface Temperatures

The difference between the room temperature (T_r) and the last set of T_i values (Figures 13 and 14) also points out the need to perform a last set of simulations to find out the final values for the surface temperatures of the walls that face the courtyard (by TRNSYS) and the air temperature in the courtyard (by ENVI-met). These values provide a key factor to determine the level of thermal comfort in the courtyard (namely the air and mean radiant temperatures that could be experienced in that space).

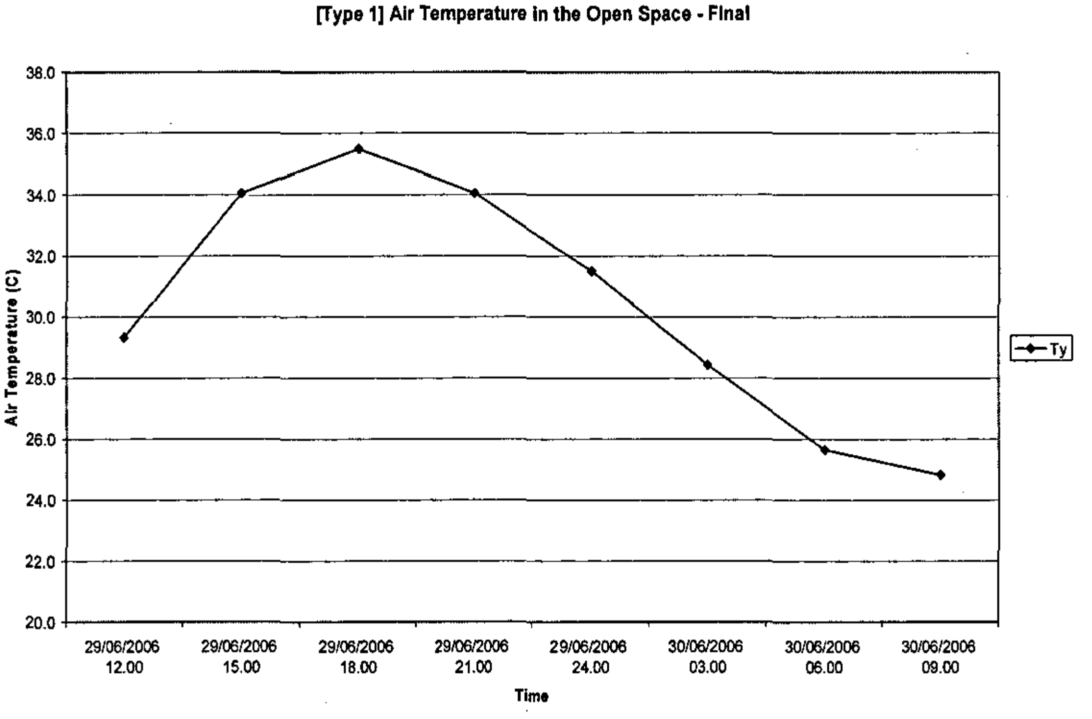


Figure 17. Final air temperatures in the courtyard after iterations

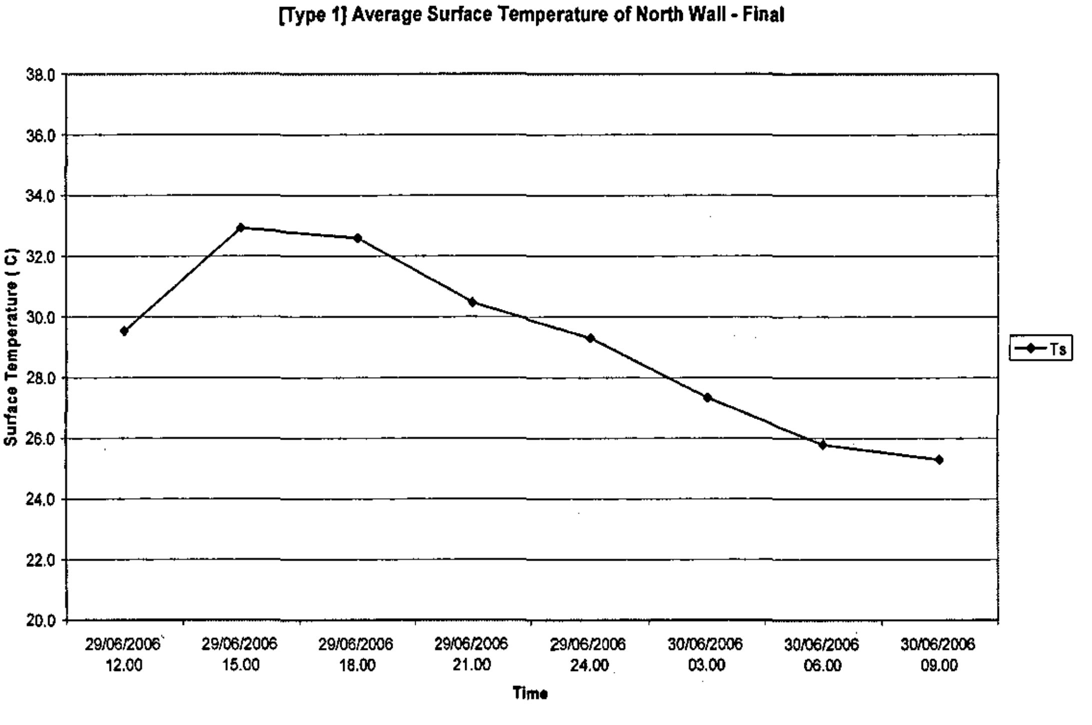


Figure 7. Final surface temperatures for one of the walls in the courtyard

4.7. Assessing Thermal Comfort in the Courtyard

Outdoor thermal comfort is a field of knowledge that is still largely under development. A few indices have been introduced to deal with this situation, each has its limitations (Ali-Toudert 2005). For the purpose of this study, the PET value index (Höppe 1999) has been adopted as it has been found to be more accurate than most of the others, at least for subjects in sedentary conditions. Figure 19 shows an example of the PET values calculated for building type 1 for a March afternoon.

These values are calculated at a height of 1 m above the ground for a 1 metre by 1 metre grid across the courtyard (see Figure 19 for an example). To judge whether this specific time of the day is thermally comfortable or uncomfortable, the criterion that was adopted was as follows. If the number of useable squares of the grid equalled or exceeded one third of the total number of the squares in the grid at a certain calculation time, then that particular time would be referred as "comfortable". All other observation times, where there is not enough useable area in the courtyard,

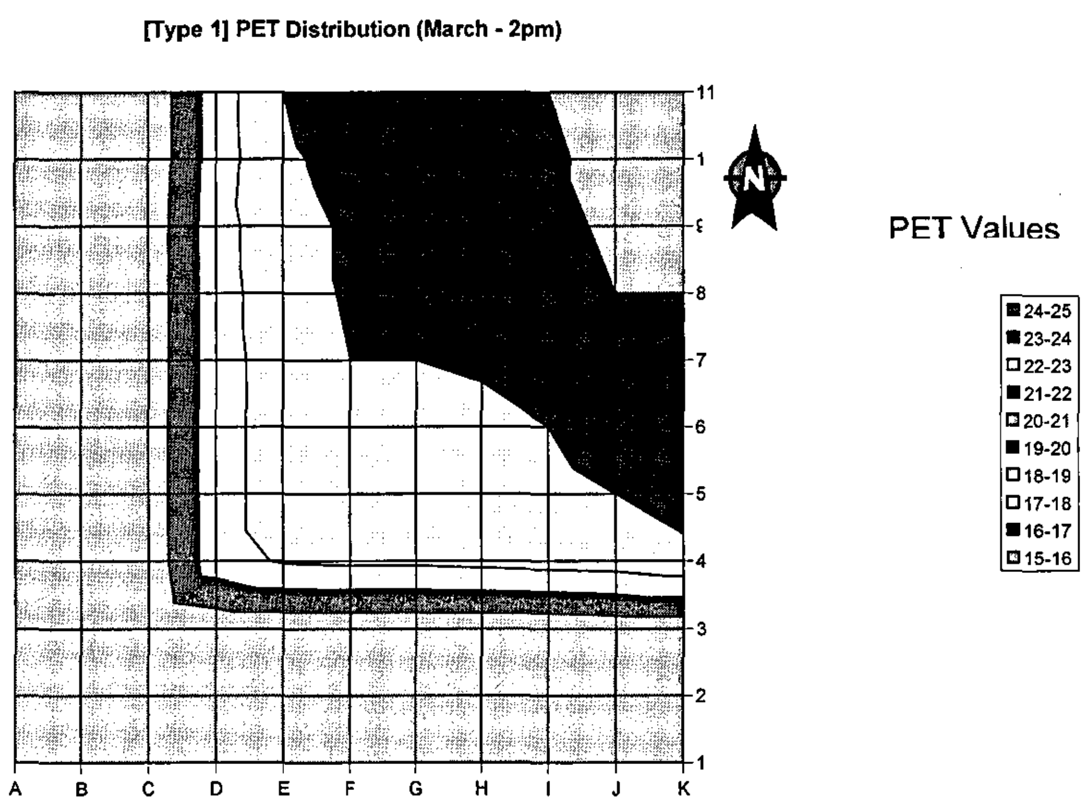


Figure 19. A sample set of PET values accross the plan view of the courtyard in Type 1

were considered thermally uncomfortable. "Usability" was also defined as being located in the PET range of 18 to 23°C which corresponds to the range of -0.5 to +0.5 on the PMV scale. (Matzarakis 1999).

Figure 20 shows the total number of comfortable hours in all six house types during a normal year and is another key factor that can be used to select the most effective house type. In this case house design Type 6 offers the greatest number of hours of

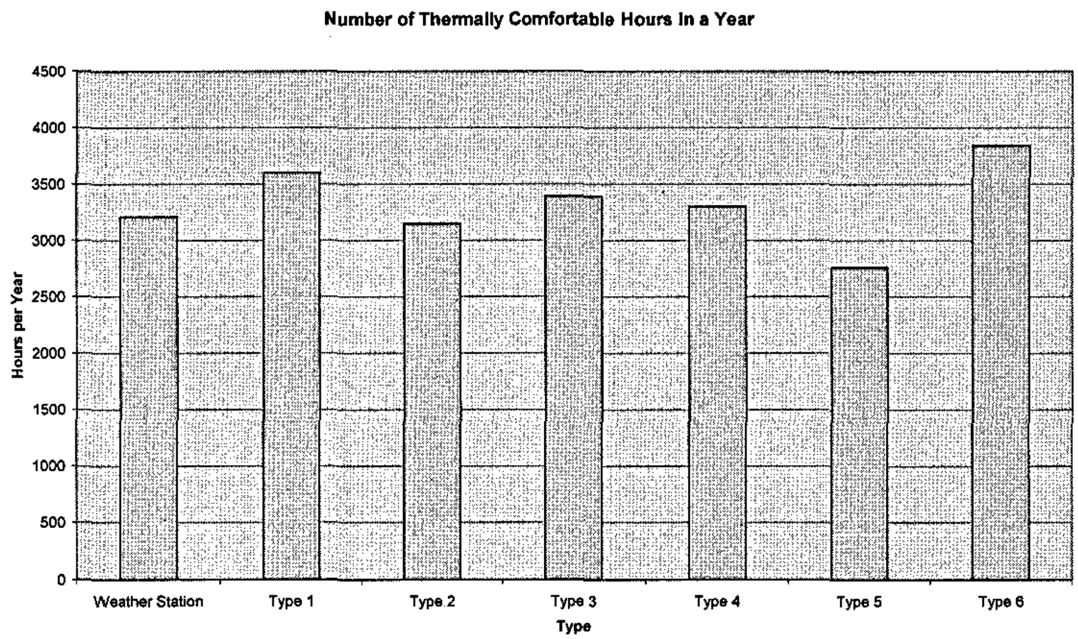


Figure 8. Comparative outdoor thermal comfort of all house types

outdoor thermal comfort as experienced in its courtyard and surrounding open space.

5. Conclusion

This paper has reported on the establishment of links between two simulation programmes (TRNSYS and ENVI-met) for the purpose of describing the integrated thermal performance of buildings and an immediately adjacent outdoor space (a yard or a courtyard). The complexities involved have been described and techniques for overcoming them have been explained.

The combination of simulations obtained is capable of predicting heating and cooling loads of the buildings in question together with the outdoor thermal comfort that might be expected in their adjacent outdoor spaces. For a range of typical house design types, a ranking in terms of these metrics has been presented. Work is continuing to develop the technique into a decision-making tool for selecting house designs, inclusive of urban layout, cost-effectiveness and social acceptability for the respective cultures.

References:

1. *Ali-Toudert, F (2005), Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate, Ph.D. Thesis, University of Freiburg, Freiburg, Germany.*
2. *ASHRAE (2004), Standard 55 - Thermal Environmental Conditions for Human Occupancy, ASHRAE Inc., Atlanta, USA.*
3. *Gooje, V (2003), Courtyard Performance; Geometry and Solar Influence, Proceedings of the Solar Conference, Austin, USA, 21 -26 June 2003.*
4. *Heidarpour, A (2002), Experiments on the Environmental Effects of Traditional Residential Architecture (in Persian), The Scientific Magazine of Civil Engineering Department of Isfahan University of Technology, Vol. 2, No. 11, pp 17-28.*
5. *Heydari, S (2000), Thermal Comfort in Iranian Courtyard Housing, Ph.D. Thesis, University of Sheffield, Sheffield, UK.*
6. *Höppe, P (1999), The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, International Journal of Biometeorology, Vol. 43, No. 3, pp 71-75.*
7. *Matzarakis, A and others (1999), Applications of a universal thermal index: Physiological Equivalent Temperature International Journal of Biometeorology, Vol. 43, No. 2, pp 76–84.*
8. *Merghani, A (2001), Thermal comfort and spatial variability in courtyard houses in hot dry climates, Ph.D. Thesis, University of Cambridge, Cambridge, UK.*
9. *Olgyay, V (1963), Design With Climate - Bioclimatic Approach to Architectural Regionalism, Princeton University Press, Princeton, USA.*
10. *Ratti, C and others (2003), Building Form and Environmental Performance; Archetypes, Analysis and an Arid Climate, Energy and Buildings, Vol. 35, No. 1, pp 49-59.*
11. *Solar Energy Laboratory (2006), SEL Publications, http://sel.me.wisc.edu/publications/publ.html, The Website of the University of Wisconsin, Madison, USA.*
12. *Tavassoli, M (1983), City Planning in the Hot, Dry Climate of Iran. In: Golany, G (ed), Design for Arid Regions, Van Nostrand Reinhold Company Inc., New York, USA.*
13. *Tropical Advisory Service (1966), Climatic Design, Report prepared for the Ministry of Public Building and Works, London, UK.*