OPTIMISING COURTYARD HOUSING DESIGN FOR SOLAR RADIATION WITHIN DENSE URBAN ENVIRONMENTS

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A Thesis submitted for the degree of
Doctor of Philosophy

School of Architectural Studies
University of Sheffield

2001

TO MY PARENTS,
AND IN MEMORY OF
MY GRANDMOTHER,
WITH LOVE.

DECLARATION

As required by the regulations for research students, I declare that this thesis in its entirety is my own work and includes nothing that is done in collaboration.

Where other sources of information have been used, there are acknowledged in parentheses, and where necessary, they are referred to specifically in the text of the thesis.

I also declare that neither the thesis submitted nor any part of it is substantially the same as any that I may have submitted for a degree or diploma or other qualification at any other university.

ACKNOWLEDGEMENTS

First of all, I should like to thank to my supervisor, Dr. Adrian C. Pitts, who has been always supportive with his wide-ranging experience, great insight and patience during my period in the School of Architectural Studies.

Dr. Robert J. Peckham provided much needed advice at the beginning of the research for my understanding in the computer programs, Shadowpack P.C version 2.0; Dr Stephen Sharples for providing valuable information on the programs, and I am pleased to acknowledge their help.

I would like to thank to the school's entire staff including those in the General Office, and especially Mrs. Hazel Hall who has been much help to me in every respect. Particular thanks to my friends, Elena Douvlou, Louie E. Gyoh and Tom Hockley.

The CVCP's ORS Committee, U.K, provided the funding for this research and I am grateful for its support.

I am happy to thank to all my teachers, friends and colleagues in Korea who have provided encouragement throughout. I also would like to thank all my family, particularly Hyun-Jeoung, Yoon-Hee and Joo-Hee, whom all my inspirations come from.

My special thanks to my parents-in-law for their continued support and encouragement whenever I felt discouraged through the times.

Finally, I am deeply indebted to my beloved wife, Jae-Young, who has provided the incentive, the time and love, and my wonderful son, Yoon-Sung, from whom I am truly blessed to have the support.

ABSTRACT

The potential of energy-conscious traditional design of dwellings has been recognised with its direct and sometimes sophisticated response to local climatic conditions in recent years. Courtyard forms, which provide heat, light, ventilation and other functions for buildings surrounding it, are found in many high density urban environments around the world.

This current study focuses on one of the solutions which can contribute to embodying the energy-conscious tradition. As an issue of how buildings respond to the different climate arises on a global scale, emphasis is placed on regional urban courtyard housing, for which design proposals are made, with special reference to Seoul, Korea (latitude 37.34° N). Apart from acting as climatic modifiers through solar access, courtyard housing forms can offer spatial and visual amenities to otherwise monotonous urban plan buildings.

The aim of this study is to gain an understanding of the relationship between courtyard design and solar radiation in a densely built housing development. The parametric study examines the possibilities of varying housing layout factors in courtyard design, such as housing density, plot dimension, housing development scale and housing orientation, thereby suggesting guidelines for suitable ranges of the design parameters of courtyard housing. By these means, a density objective in urban area can be achieved with certain parameters with a potential to form energy-conscious courtyard design.

Solutions for optimising the use of solar energy in courtyard housing layout in future housing development are categorised into (1) efficient layout planning, which include the range of optimum use of the housing layout factors and storey height under land use policy, and (2) passive courtyard housing form, which respond to urban housing layouts. Implications of the design strategies for planners, designers and local authorities are then outlined, including design guidelines.

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Chapter 1

Introduction

1-1. Formulation of the Problem

1-1-1. Background study

It is now recognised that the climatic-responsive tradition of housing forms, which were adapted to the local climate and the needs of the occupants, can be seen around the world. A large number of studies have now been completed to demonstrate the benefits of reduced thermal discomfort within buildings which conform to a traditional style and use traditional material. Also work done in Korea has shown some of the advantages and disadvantages of traditional forms of building (K-H. Lee, 1996, 1997). In recent years, however, architects in many countries have abandoned the link between climate and building; this may be either because of desire by architects to adopt a more international style or because of the availability of cheap energy to power artificial heating, ventilation, air conditioning and lighting systems. A further, and possibly the main, influencing factor has been the need to house large numbers of people at high density in fast developing urban areas.

Among the house design of the energy-conscious tradition, the potential benefits of introducing courtyard housing are now widely acknowledged (Mohsen, 1978; Meir et al, 1995; Pitts et al, 1997). The courtyard house has been a characteristic and dominant traditional building type in the Asian region, both hot-humid and cold zones. Many traditional courtyard housing forms found in the region show that house design has been integrated with social, cultural, technical and environmental factors. Various ways of embodying the factors were realised in traditional houses over several centuries so that with the concept of having spaces facing inwards, a courtyard was introduced to meet the society's demand and to ease climatic problems. Apart from acting as a form for controlling microclimates through solar access and wind patterns (for both the cooling and heating periods), courtyard spaces accommodated in housing developments can embody design elements used in traditional Korean architecture, offering spatial amenities to otherwise monotonous box-like urban housing buildings. A study of various housing forms suggests that one building form which might be exploited to provide both reasonably high density and comfort, is the courtyard form (De Chiara et al, 1984).

The courtyard is an important architectural element in Korean traditional houses and is commonly found in urban environments. Additionally, the use of enclosed and attached courtyards is often associated with pleasant environments. Dating from the 1930s, modified courtyard types of houses, for example, those arising from traditional houses, have been mass produced in the urban areas of main cities as a form constructed to meet the needs of improving the physical environment in dense areas, and to reduce house shortage problems (I-H. Song, 1990; J-Y. Park, 1996). However a turning point took place in the middle of the 1960's when the concept of building apartment blocks seemed to be an ideal solution for the problems created by continuing urbanisation. Since then, urbanisation driven by a desire to adopt a more international style seems to reflect a complete disregard for local climatic conditions. Of possible solutions to tackle the problem caused by adopting the international style, which was induced to cope with land use shortage and resulted consequently in limitations on house size, the suitability of reintroducing the courtyard house as an alternative type to mitigate urban environment is justified.

In addition, there has been a survey of housing types in terms of national distribution implying general preference to live in the type of detached housing dwellings for Korean (Korean Ministry of Construction, 1999). Considering the inevitable current of introducing high-rise apartment blocks due to the shortage of land for housing uses, detached types of housing have become and will continue to be popular with improvements in life style. That is, in urban areas, people tend to live in apartment blocks because of the needs for density but would prefer detached housing. Therefore, solutions are also sought in an attempt to suggest how hybrid forms of detached housing building incorporating traditional elements can improve housing developments in dense urban environments with special reference to Seoul, Korea.

1-1-2. Climatic responsive courtyard design

It is generally suggested that, the level of thermal comfort in a courtyard space is determined by the microclimatic forces acting on it, most notably those of solar radiation and wind (Meir et al, 1995).

(1) Solar radiation; In courtyard forms, the proportion, the height and the orientation of the courtyard are the main influencing factors that control the amounts of solar radiation loads on the courtyard facades. For a hot-dry climate, Olygay (1963) suggested that the optimum form which loses the minimum amount of heat in winter and loses the minimum in summer is a plan with inward looking scheme. Mohsen (1979) who investigated the relationship between solar radiation and courtyard's orientation / geometry indicates that, for optimum summer conditions, the deepest and the most elongated courtyards in the E-W axis were most favourable. Also this includes that, for a single storey courtyard, the proportions that satisfy the minimum irradiation load in summer differ from the geometry which best satisfies maximum irradiation load in winter.

(2) Wind; Need for air movement through the courtyard is critical to human thermal comfort. Namely, natural ventilation and night-time radiative cooling are mechanisms that were claimed to have been extensively used in courtyard buildings to provide cooling. It is believed that the height and orientation of courtyard is closely related to the performance of wind-driven

ventilation. Leung et al (1981) suggested that the shallowest form is the logical design to enhance wind-driven ventilation. The geometry of the courtyard, i.e. aspect ratio, are likely to affect the radiative cooling performance of the courtyard at night. In addition, Bensalem (1991) concluded that the largest courtyard sizes did not particularly record the best ventilative performances in contrast to what is generally believed. Finally, Meir et al (1995) points out that the orientation of main courtyard facades can be a determining factor in order to improve thermal behaviour, while orientating them irrespective of solar angles and wind direction may create thermal discomfort inside courtyard facades.

1-2. The Purpose and Scope of the Thesis

One of the most advantageous factors of urban courtyard forms as a detached housing type is their contribution towards enhancing land-utilisation as well as providing visual and psychological amenities. Martin and March (1966) described that, among various building forms, the courtyard form of densely built urban development make so efficient use of land that they can ensure street continuity and sunlight.

In environmental housing design, one of the main environmental determining factors for courtyards is the solar radiation penetration. In urban housing development, in general, as housing density increases, it becomes more difficult to optimise solar heat gain during the heating season, mainly due to constraints in allocating plot areas for housing use. A further problem is particularly profound in courtyard housing where the intensity of land-use related to the amounts of solar radiation available, affects directly the configurations of the courtyard inside. Though it is not an important issue for low-density housing developments in terms of land-utilisation, it is obvious that an understanding of relationships between courtyard housing and solar access in high-density development for urban courtyard housing is much needed.

Only a few studies have attempted to define the relationship between conflicting factors, density and solar radiation, for urban housing forms (Ó Catháin, 1977, 1978, 1981; J-T. Kim, 1997; Cadima, 2000). Ó Catháin suggested that, in order to define the implications of density and overshadowing for passive solar housing, the relationship between plot dimensions, density, the proportions and their effects as constraints on the built form should be taken into account by local authorities. Therefore it is timely to study the relationship through an examination of various housing layout factors, which need to be further developed for urban courtyard housing in particular. This is particularly appropriate in Korea under current land-use policy, i.e. building regulation codes.

The aim of this study is to gain an understanding of the relationship between courtyard design and solar radiation in a densely built housing development. It examines the possibilities of varying certain housing layout factors in courtyard design, such as housing density, plot dimension, housing development scale and plot orientation, thereby suggesting guidelines for suitable ranges of the design parameters of courtyard housing. By these means a certain density objective in urban sites can be achieved whilst better solar access is maintained. The outcomes of the analyses may be used to generate design proposals for urban courtyard housing developments where an understanding of the relationships between the land-use intensity and adequate solar heat gain is much needed.

1-3. Structure of the Thesis

The parametric and comparative study consists of seven chapters.

The first chapter, an introductory chapter, describes the problem from which this study was inspired and suggests the approach.

Chapter two is divided into two parts, the climate condition and the housing type of Korea as a background study. The former describes general features of the climate condition including a series of climatic schemes. An effort has been made in classifying general climate zones. Based on this, the selection of the heating and cooling period is carried out in order to provide seasonal criteria for the computer analysis. The latter examines the various types of traditional houses and housing layouts. It also gives a general overview of the relationship between typical folk houses and urban courtyard houses. As the urban courtyard house has remarkable features in the formation of urban town planning and housing design, attempts to incorporate hybrid courtyard forms with contemporary house building are shown as ideas establishing the energy-conscious tradition for densely built urban areas.

In Chapter three, a series of density expressions, by which the relationship of housing layout factors, i.e. housing density, plot dimension, housing development scale and plot orientation, and net courtyard areas with their corresponding solar gain can be identified, are developed. It is intended to state the scopes of the housing layout factors which are more beneficial in ensuring relatively sufficient solar access into the courtyards whilst maximising land-utilisation in a densely built urban area. In order to derive the expressions, firstly, current land-use policies that are directly related to housing layout density in terms of building regulation codes are examined. As there needs to be a limit to the number of cases, simple theoretical models of housing layout incorporating courtyards in urban development are modelled by using criteria based on land use data supplied by the policies. Then, the density expressions for the two developed model layouts with parallel streets running E-W and N-S are suggested.

Chapter four focuses on a computer simulation tool named Shadowpack package-P.C.version 2.0, for the assessment of solar radiation on the courtyard models. The computer tool is devised for general use in assessing the amounts of solar radiation of building facades of any proportion, size and orientation at any location and time by creating a 3D model of building models. The key programs included in the package are ICON, SHADEN, GLOBAL and ISOSUN. All of these programs work interactively to assess the solar gains of building facades.

Chapter five is devoted to the demonstration of results of parametric and comparative studies including the relative sensitivity of the housing layout factors for urban courtyard housing models. The effect of varying the housing layout factors on the variation both in net useable courtyard area and corresponding amount of solar radiation is compared and analysed. A range of values for each parameter for the housing layout factors is chosen so as to cover the reasonable variations in urban housing developments. Brief descriptions for each housing layout factor and its ranges that make most use of utilising solar radiation are given. The scopes of solar variations in solar radiation from the analyses are expressed graphically based on heating and cooling periods.

The evaluation and interpretation of the analyses are given in Chapter six. The evaluation is conducted in two major categories. First, the relationship among the housing layout factor, net courtyard area and solar radiation is assessed on the basis of changing building height. Second, various modes of solar radiation strategies are examined in order to produce design combination by suggesting relative advantages in controlling for housing density and solar access. Furthermore, optimum ranges of urban courtyard housing design corresponding to each housing layout factor are proposed. Special emphasis is laid on certain housing layout factors which show much better potential than others.

In Chapter seven, conclusions and recommendations on urban courtyard housing design are summarised. Implications of the design strategies for related people are then outlined. The need for further work along with the limitations of this work is emphasised.

Chapter 2

Climatic Approaches to the Design Principles of Courtyard Houses

2-1. Introduction

A large number of studies have been completed to demonstrate the relationship between humans and their environment. Of the works done on the relationship, climatic determinism has clearly shown some of the links between the buildings and climate. Although climatic determinism does not fully explain all the aspects of forming buildings, this may be at least used to realize a systematic approach to architectural design (Rapoport, 1969).

As energy costs rise and the global consequences of inefficient use of fossil fuels become widely known, there is requirement to return to more traditional, environmentally sensitive architectural design. The term, energy-conscious design, means the design method devised for adapting architecture to its local climate. It provides a healthy environment by controlling the utilisation of natural energies. Recent works in Korea have shown some of the advantages of traditional forms of building (K.H. Lee et al, 1996, 1997). They concluded that adapting to the surrounding environment that has very distinctive cultural and climatic characteristics has helped develop Korean traditional architecture.

From the viewpoint of energy-conscious tradition, the courtyard form also utilises heat, light, ventilation and other functions to buildings that surround it. Its structure, size and shape play an important role in modifying climate

(Bensalem, 1991). The courtyard form is found to be one building form which provides comfort for human being inside buildings in high-density urban environments.

In this chapter, the study aims to analyse the particular climate conditions and classify the climatic zones of Korea. In addition, architectural characteristics of housing types are examined in order to introduce the courtyard form that provides an alternative solution to maximise land-utilisation. Various modes of courtyard forms corresponding to town layout structures are studied. It will aim to suggest how hybrid forms of courtyard housing incorporating traditional elements can improve urban development.

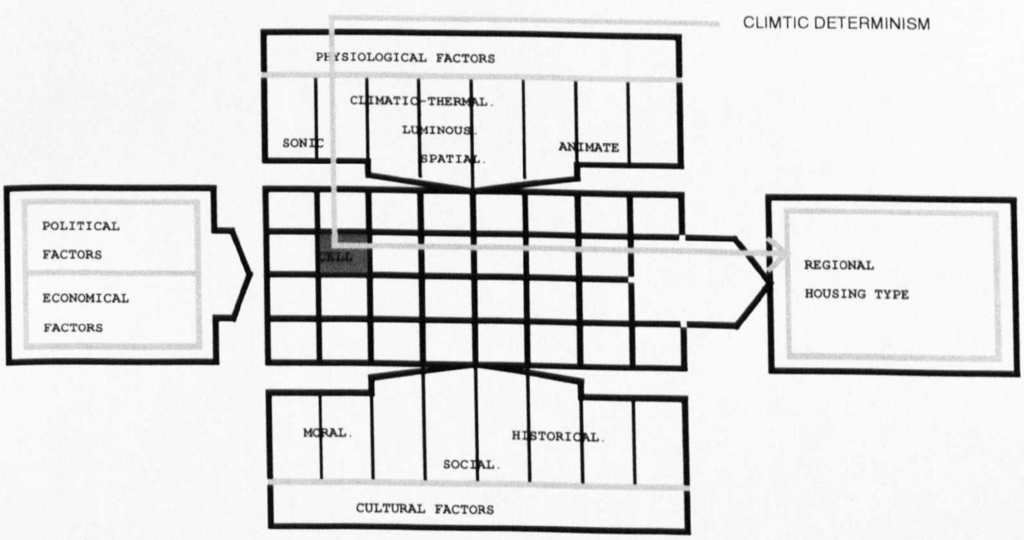


Figure 2-1. Schematic diagram on the relationship between regional housing type and environment

2-2. Climate of Korea

In the following sections, the climate of East Asia is examined in general and that of Korea in particular. Though different researchers have provided a range of different climate classifications, general definitions related to Korea have been identified. The general climate features are also compared with other regions of the world in order to examine other cultural responses to similar climates.

2-2-1. Climatic Zone

2-2-1-1. Main features

Climatically, Korea lying between 33-43 deg. N of latitude and 124-131 deg. E of longitude is defined as a zone being humid and warm-to-hot in summer and cold to very-cold in winter. It is characterised, in general, by the high capacity of the air for vapour content with rising temperature. Therefore the amount of water vapour borne in the atmosphere brings out the need to provide ample natural ventilation in summer, and it implies the most difficult condition to ameliorate by design (Gavieta, 1991). The predominance of partially cloudy sky shows that considerations of not only the direct component of solar radiation but also reflected and diffuse components would be necessary in this hot-humid and cold zone.

Summer daytime temperatures are often above 30°C accompanied by the occasional high intensities of solar radiation coupled with high humidity. Cold winters have temperatures often well below the freezing level thus indicating the wide range of daily temperatures are common features of this type of climate. Rainfall is highest in the summer, the winds in winter are mainly from the north and in summer mainly from the southeast.

2-2-1-2. Seasons

Korea borders on China on the north and Japan on the east, having seas between the countries. Inland Seas bounded by them modifies the seasonal patterns of local climate. Two main seasons and other two transitional seasons are found as follows.

① Summer (June to August)

② Winter (December to February)

③ Spring & Autumn (March to May, and September to November)

1. Summer

The summer period mainly consists of the rains in the early summer and high intensities of solar radiation resulting in the wide range of daily temperatures.

(1) Rainy spell in the early summer

The rainy spell in summer features mostly cloud with high humidity levels. Nearly 50-60% of the amount of rainfall, which is equivalent of 1200-1700mm according to geographical patterns, on average a year is recorded during this period. After the rains disappear, temperature rises gradually above 30-35°C in the daytime.

(2) In the summer

The hottest season occurs between July to September. The high pressure from the pacific begins to establish itself over Korea and remains constant during the period. It keeps temperature rising to very high level over 30°C. Thus it creates the most unpleasant thermal conditions combining with the high level of humidity reaching normally over 70-80%. The highest temperature recorded was 40°C in southern parts of Korea in August 1942. In general, temperature shows its peak in July and August over a vast area of the country. The fact that the mean monthly temperature during this period varies from about 28-30°C in all areas implies narrow temperature ranges marked between northern and southern region. The duration of the daily sunshine is ten to twelve hours a day. In addition, typhoons accompanied with rainfall occur from the Pacific approaches on occasions and periodic winds blowing from south–east raised by the wet monsoon prevail. Relative humidity level marks its peak from July to August after the rainy season.

2. Winter

The weather in winter is characterised by a long severe cold and dry period, arising from the Siberian influence, with temperature often below 0°C. For instance, the lowest temperature of –43.6° C on 12 February 1933 was recorded in a northern end. Some mountainous regions alongside of eastern coastal lines shows temperature ranges from –20 to -30° C, whilst monthly mean temperatures of cities, Seoul as an example, range from –1 to -5° C. It is caused by the move of the prevailing westerlies developed by radiant cooling effect from an increased number of frozen areas in Siberia. In general, the mean monthly temperatures during the months mark from 0°C to -7°C. January is the generally coolest month which results in large temperature differences between summer and winter.

Periodic winds blow from the northwest and are predominant over Korea from November to February as high pressure area occurring over Siberia. When high-pressure system diminishes, periodic winds become more pronounced. Geographical and topographical conditions give rise to some local modifications to the wind direction. Snowfall is heavy in some parts of higher mountains, even in the plain areas of the northern region when it is lied on the passage of air mass.

The annual snowfall on some island and northern area averages 200 cm, and southern area and coastal region being 50-70 cm. Daily sunshine duration ranges from seven to eight hours during the winter.

3. Transitional periods

(1) Spring

This season appears between March and May. Generally a mild and balmy condition features during this period. However, the intermittent high and low atmospheric pressures that cause unsettled weather condition begin to appear at intervals of three to four days. The seasonal mean temperature records are between 5-23°C. Relative humidity level remains constant normally between 60-70% but sometimes is rarely observed below 30%.

(2) Autumn

High atmospheric pressure dominates during this period to form a most pleasant weather belt with average temperatures of 16-22°C. Relative humidity is from 50-70%. The daily duration of sunshine becomes decreased as the altitude of the sun gets lower.

2-2-2. Schemes for Climatic Classification

2-2-2-1. Schemes

Schemes for the methods of climatic classification are varied by use for purpose and by criteria set for grouping. In other words, schemes dividing climatic zones depend mainly on different views of selecting climatic variables such as climatic data and indices. The basic climatic elements that consist of the climatic data and indices can be defined by (1) air temperature, (2) atmospheric moisture including clouds, fog, humidity and precipitation and (3) pressure and winds (Meyer, 1963). Of various schemes, Köppen's classification, which are the most widely adopted classification, suggested from the macro-climatic viewpoint and four other schemes made from the micro-climatic viewpoint is presented as below.

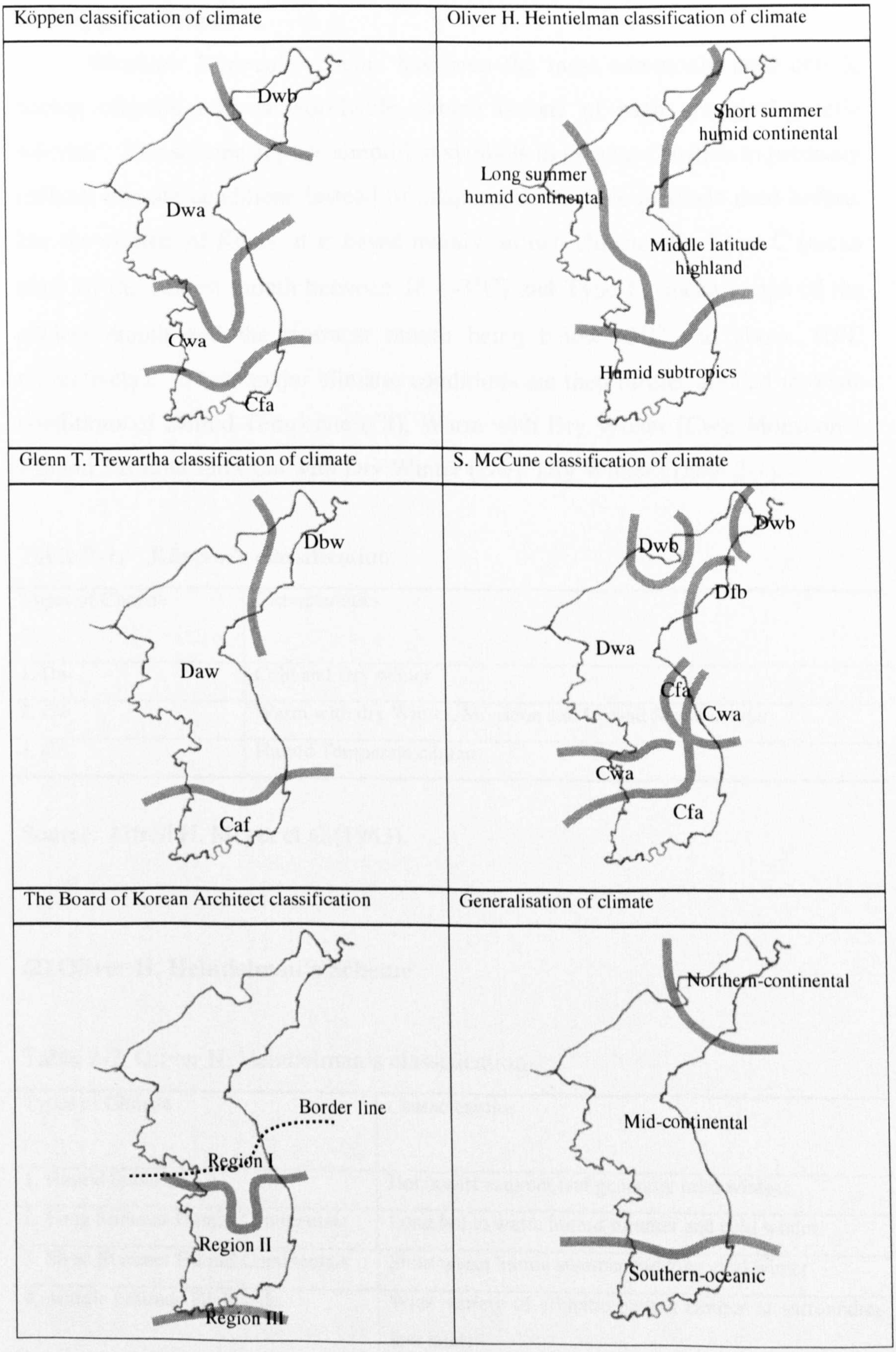


Figure 2-2. Climatic classification suggested by the schemes

(1) Köppen's Scheme

Wladimir Koppen's scheme has been the most commonly used one in zoning climatic regions worldwide, which is one of such empirical-genetic scheme. The scheme applies simplified symbols to the classification to precisely indicate climate conditions instead of adapting descriptive methods used before. For the climate of Korea, it is based mainly on two climates i.e. Type C (mean temp of the coldest month between 18~ -3°C) and Type D (mean temps of the coldest month and the warmest month being below -3°C and above 10°C respectively). These major climatic conditions are then further divided into sub conditions of Humid Temperate (Cf), Warm with Dry Winter (Cw): Monsoon + Upland Savanna and Cold with Dry Winter (Dw): Dry Winter (Table 2-1).

Table 2-1. Köppen's classification

Types of Climate	Characteristics
1. Dw	Cold and Dry winter
2. Cw	Warm with dry Winter, Monsoon and Upland Savanna type
3. Cf	Humid Temperate climate

Source: Alfred H. Meyer et al (1963).

(2) Oliver H. Heintielman's Scheme

Table 2-2. Oliver H. Heintielman's classification

Types of Climate	Characteristics
1. Humid Subtorpics	Hot, moist summer and generally mild winters
2. Long Summer Humid Continentals	Long hot to warm humid summer and cold winter
3. Short Summer Humid Continentals	Short warm humid summer and long cold winter
4. Middle Latitude Highlands	Wide variety of climatic pattern similar to surrounding low lands

Source: Oliver H. Heintielman et al (1968).

Oliver H. Heintielman gives the classification for the world into 14 types of conditions. Based on this, the scheme identified four primary regions for Korea with climatic and geographical data such as temperature, precipitation, winds and surface features. According to his classification, the climatic zones are categorised into; humid subtropics, long summer humid continentals, short summer humid continentals and highlands (Table 2-2).

(3) Glenn T. Trewartha's Scheme

Glenn T. Trewartha's scheme utilises a number of climatic data and indices together with geographical data at a place to establish more precise climatic zones. This classification is modified and simplified from Köppen by means of recognising temperature and precipitation as the two elements of paramount importance. Compared to Köppen whose classification identifies five main groups of world climate, this has six main climatic groups, i.e. Tropical rainy, Dry, Humid meso-thermal, Humid micro-thermal, Polar and Highland climate. Then, climatic zones for Korea are further divided into subsections, i.e. Dc for northern and middle areas and Df for southern areas. A detailed description on his classification of climate is given in Table 2-3.

Table 2-3. Glenn T. Trewartha's classification

Types of Climate	Characteristics
1. Dbw	Humid Temperate Continental, Cool Summer and Cold-dry Winter
2. Daw	Humid Temperate Continental, Warm Summer and Cool-dry Winter
3. Caf	Humid Subtropical; Warm Summer and Mild Winter

Source: Glenn T. Trewartha (1968).

(4) McCune's Scheme

From the viewpoints of micro-climatic classification on Korea, McCune's scheme is also based on same criteria as Köppen applied to his scheme in a way of dividing climatic zones by introducing a climatic element, mean monthly temperature. The scheme zones Korea into eight based on six types of climate symbol shown in Table 2-4. McCune has adapted a criterion to divide cold (D) and warm (C) conditions on a basis of a period of more than 5 months showing mean temperature below 0°C. He reckons that winter representing long and severe period is an important period determining the major regional difference of the climate thus influencing the possibility of having double-cropping a year in agriculture.

Table 2-4. S.McCune's classification

Types of Climate	Characteristics
1. Dwb	Cold and dry; humid, severe winter-short summer, forest and prairie lands
2. Dwa	Cold and dry; monsoon phase
3. Dfb	Cool and humid; humid, severe winter-short summer, forest and prairie realm
4. Dfa	Cool and humid; humid severe, occasionally mild winter-long summer, forest and prairie lands
5. Cwa	Warm and dry; humid mild winter, forest and prairie realm
6. Cfa	Humid temperate; humid, mild winter, forest and prairie realm

Source: K-S. Kim et al (1982).

(5) The Board of Korean Architects's Scheme

The board of Korean Architects has presented the classification of climatic regions only applicable to South Korea, taking into account of the thermal insulation standard of the house envelope. This classification is based upon solar radiation, wind, cloudiness, altitude, mean monthly temperature. It also accepts population as one of the expression of the totality of a climate, so that three climatic boundaries – Region I, II and III - are selected. The Board's method of adopting those climatic features is to provide the optimal standards for the insulation installed in the building types based on heating degree-days. Therefore the classification of climatic zones is based on Korean administrative boundaries in order to suggest optimum insulation levels according to each province for convenience.

Table 2-5. The Board of Korean Architect's classification

Types of Climate	Characteristics
Region I	Heating degree-days over 3000
Region II	Heating degree-days between 3000-2000
Region III	Heating degree-days below 2000

Source: J-O. Koo (1988).

2-2-2-2. Summary: Climatic zone

The diverse classification methods defined by the schemes are shown in Figure 2-2. Climatic analyses of the schemes show, in general, that the weather in winter is characterised by a long severe cold and dry period, arising from the Siberian influence; in summer a very hot and humid period arises from the South Pacific Ocean. Thus it is possible to group the climatic conditions stated above into three schematic zones according to the degree of the hottest and coldest periods. The climatic zones defined from the schematic viewpoint are described as (1) Northern Continental zone: cold winter and mild summer, (2) Mid-Continental zone: cool winter and hot summer and (3) Southern Oceanic zone: mild winter and hot summer.

Three main cities that stand for their associated climatic zones defined in above section are selected and their most relevant characteristics are:

Climatic type	Description	Location: city	Latitude
Northern continental	Cold winter with mild summer	Unggi	42°19′N
Mid-continental	Cool winter, mild to hot summer	Seoul	37°34′N
Southern oceanic	Mild winter, hot summer	Pusan	35°06′N

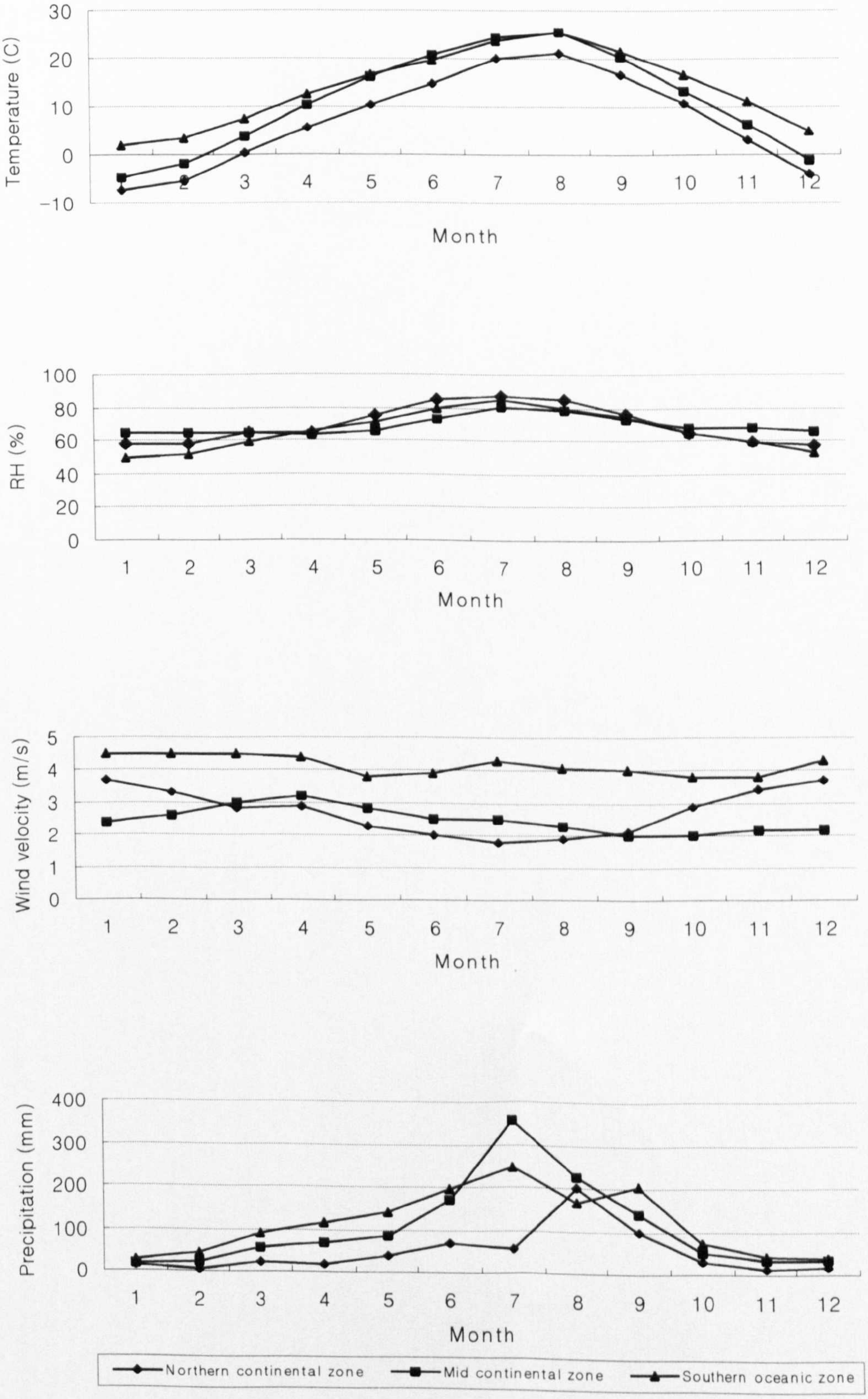


Figure 2-3. Major climatic zones and conditions of Korea

Source: Adrian C. Pitts et al (1997).

1. Northern Continental zones

(1) Highland zone

Highland zone covers mountainous regions placed over an altitude of 1,000 metres. The annual mean temp varies between 4 - 6°C that mark the lowest of the mean temp in Korea thereby implying a long severe cold winter. The coldest month is January with the minimum monthly mean temp of –20 ~ -14°C and warmest month being July and August with mean monthly temp over 20°C. Rain is scarce recording 700-900mm a year.

(2) Northeast coastal zone

This zone includes major part of northeast area along coastline and a part of mountainous districts. Minimum annual mean temp ranges –10 ~ 6°C. Annual rainfall being between 600 - 700 mm on average.

2. Mid-Continental zone

(1) Mid-west coastal zone

The zone, acts as a buffer between south and north region from the viewpoint of climate and consists of plains and plateaus. It is subject to a wide range of temp fluctuation. Annual mean temperature records about 10°C. Rain 1,100 ~ 1,200 mm at most places. Sunshine moderate, 10-11 hours per day duration in June/August.

(2) Mid-west inland zone

The mid-western part of southern region of Korea characterised by hot summer, cool winter. August is the hottest month with mean temp above 25°C and mean monthly maximum temp of 30.5°C. Coldest month January at below -7°C. Rain 1000 ~ 1200mm on annual basis indicates having much more than other regions.

(3) Mid-east coastal zone

The ocean climate influences this zone facing to the East Sea that shares its border with Japan. The region shows January mean temp of – 2 ~ 7°C that marks higher mean temp than other regions thus having less cold climate in winter. Annual rainfall averages 900 ~ 1300mm that is highest among regions along east coastal line.

(4) Parts of south and mid east coastal zone

The annual temperature of major parts of south inland and coastal zone marks 12 ~ 13°C. Winds blowing over mountainous district become dehumidified and causes somewhat high mean temp of 1 ~ 0°C as compared to mean temp of 1 ~ 3°C recorded in other regions on the identical latitude.

3. Southern Oceanic zone

(1) South inland zone

This zone covers the southern part of Korea including plains and mountainous districts. Maximum mean temp of about 31°C is normally measured in August. Annual precipitation level ranges between 1,000 ~ 1,200mm at most places, but for some places it reaches up to 1,300mm.

(2) Southern coastal zone

The zone covered along with coastline in southern regions. Annual mean temp of 13 ~ 14°C that indicates the highest of mean temp recorded among the regions. January temperature moderate with a range of 0 ~ 2°C. Rain records its highest marked between 1,200 ~ 1,500 mm a year.

2-2-3. Climatic Data in Urban Areas

This section aims at summarising the climatic features of Seoul of which the following investigation in the study will make main use.

2-2-3-1. Climate of Seoul

Seoul, the capital city where a series of traditional house forms are found, is situated in the mid-continental zone. The noon solar altitude is at its highest angle of 75.9° in June; 29.03° is the lowest angle in December. The highest monthly mean temperature marks 25.4°C in August. Sunrise and sunset azimuth range from 87.29° and 127.3° to 272.4° and 233.7° on June 21 and December 21 respectively. Monthly duration of sunshine ranges from a maximum of 256.8 hours for May, to a minimum of 160.5 hours for December.

2-2-3-2. Climatic data collection

The statistics period is the 30 years period from 1961 to 1990. Observation data period of less than 10 years were excluded (K.M.D, 1991).

1. Solar radiation

The data of global radiation (direct and diffuse radiation) on a horizontal surface is obtained on a regular basis from Meteorological Department. It is the monthly average of the daily observations of Eppley's Radiation recorder, and its annual average is the mean of the monthly averages.

2. Sunshine duration

The duration of sunshine for a month is the sum of the actual daily sunshine duration. The total possible duration for each month is summed on a daily basis between sunrise and sunset. The duration of sunshine of WFOs measured by Meteorological Department is calculated from observations of Jordan's sunshine recorder, and that of WOS's is obtained using Bimetal sunshine recorder.

3. Air temperature

In the 'Climatological Standard Normals of Korea', data of air temperature are given in two types: daily mean values of maximum and minimum air temperature, and monthly mean values of maximum and minimum. The daily means of maximum and minimum temperature are obtained by monthly averaging their daily values. Monthly maximum and minimum temperature are by averaging the maximums and minimums of each month over 30 years. The mercury thermometers, used for measuring dry bulb temperature, are exposed freely in the louvered screens with their bulbs at a height of 1.5 metres above the ground.

4. Precipitation

In general, the precipitation reaches a maximum in summer and a minimum in winter. The precipitation and its duration are obtained on the average of the totals of each month.

5. Relative humidity

The data presented in the 'Climatological Standard Normals of Korea' are the monthly mean values obtained by averaging the four observations of a day: The values are computed from the daily routine values from the dry and wet bulb thermometer readings using

6. Wind velocity

Observations of the surface wind of Seoul are made on hourly basis. Hourly observations on wind speed, percentage of frequency and maximum speed of each wind direction are taken with anemometer set at 10.6 m above the ground.

Table 2-6. Weather data of Seoul on a monthly basis (Lat. 37.34 deg.)

Factor \ Month		Jan.	Feb.	Mar.	Apr.	May.	June.
Solar radiation (kcal/m^2)		1720	2155	2878	3250	3792	3613
Sunshine duration (0.1hr)		1632	1651	2040	2053	2271	1902
Temperature: monthly mean		-4.9	-1.9	3.6	10.5	16.3	20.8
Temperature: mean max		8	11.6	17.8	25.1	29.3	31.7
Temperature: mean min		-14.8	-12.4	-6	0.7	7.4	12.7
Precipitation (1mm)		22.9	24.6	46.7	93.7	92.0	133.8
Humidity (%)		64	64	63	61	65	72
Wind speed On average (0.1m/s)	NE	18	21	22	24	20	18
	E	17	19	21	22	18	16
	SE	13	16	15	19	16	16
	S	16	17	20	25	21	19
	SW	25	28	34	38	33	29
	W	33	36	36	36	33	30
	NW	29	29	30	28	23	19
	N	12	14	15	14	13	13
Frequency of Wind directions (%)	NE	126	107	97	100	90	97
	E	18	24	26	43	36	45
	SE	4	5	7	14	16	17
	S	6	8	12	20	19	18
	SW	34	50	75	100	109	100
	W	161	179	184	165	179	174
	NW	96	82	65	37	30	30
	N	16	14	13	13	12	13

Factor \ Month		July.	Aug.	Sept.	Oct.	Nov.	Dec.
Solar radiation (kcal/m^2)		2958	2791	2914	2383	1772	1576
Sunshine duration (0.1hr)		1212	1496	1796	2043	1509	1473
Temperature: monthly mean		24.5	25.4	20.3	13.4	6.3	-1.2
Temperature: mean max		33.4	33.8	30.1	25.7	19.3	12.3
Temperature: mean min		17.8	18.3	10.2	2.2	-6.5	-12.5
Precipitation (1mm)		369.1	293.9	168.9	49.4	53.1	21.7
Humidity (%)		81	79	73	67	66	66
Wind speed On average (0.1m/s)	NE	20	21	19	15	17	17
	E	18	18	17	15	17	18
	SE	16	16	14	14	14	13
	S	21	20	16	16	18	19
	SW	32	33	27	26	26	25
	W	28	28	29	31	33	33
	NW	18	19	20	23	29	29
	N	11	12	12	12	13	14
Frequency of Wind directions (%)	NE	110	152	171	141	142	143
	E	45	49	60	49	37	24
	SE	23	21	16	11	8	4
	S	27	18	11	13	11	9
	SW	128	80	41	35	41	31
	W	124	111	100	126	131	143
	NW	21	27	50	71	80	98
	N	13	17	26	27	22	26

Source: Korea Meteorological Department (1991).

2-3. Development of House Form

Traditional houses in Korea date back to the fifteenth century when 'confucianism' became the dominant idea embodying the way of living for the common people thereby providing fundamental design principles to the formatting of the traditional house (H-O. Hong, 1992). In Korean architecture, the form of traditional housing types is considered to mirror climatic and social factors in its design principles by adapting the surrounding environment. K-H Lee (1996) also points out that, especially with poor building techniques and the limited knowledge of environmental control, climate seems to have a major impact on the building. It is also a general belief that traditional folk houses that belonged to the common people at the time had been adapted to the natural environment by stressing the main influences from climatic factors.

C. of Era	Period	Constituent countries	Remarks
The Paleolithic Age	Tertiary~B.C 4000		
The Neolithic Age	B.C4000~3000 B.C3000~2000 B.C2000~700		
The Bronze Age	B.C700~300 B.C300~A.D 0		
The Era of the Primary three kingdoms	A.D 0~300		Suhyel dwelling Guytlegyp Gosang dwelling
The Era of the three kingdoms & The Era of the United Shilla	A.D300~918	Baekjae Kokuryo Shilla	Appearance of 'Ondol' Appearance of 'Maru'
The Era of Koryo	A.D918~1392		
The Era of Chosun	A.D1392~1910		•The main period of study •Substantial research data
The Era under the rule of Japan	A.D1910~1945		•Modified housing type
Modern Ages	A.D1950~	North Korea South Korea	•Developed separately in either countries •Gradual extinction of traditional house

Figure 2-4. The classification of the house form according to the period of each era

Traditional folk houses show that, in spite of the variety of their plans, they share common characteristic features. Details of what the typical traditional house looks like can be gathered from the house types built in the period of the Chosun era during 1500 to 1900 (Figure 2-5). A consistency of approach to define the constraints related to climatic and social factors is strongly reflected in their design. Examples of the houses can be found in all parts of Korea.

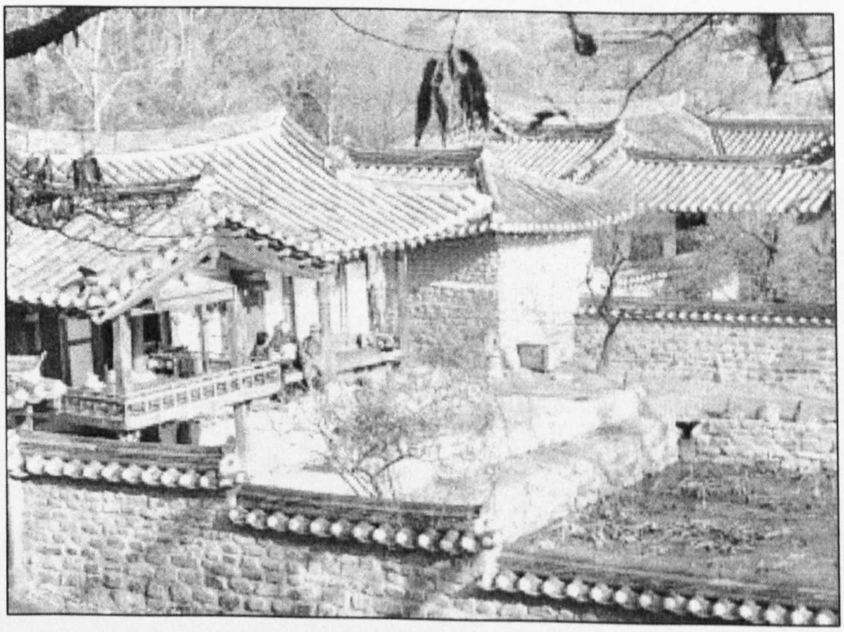


Figure 2-5. Typical view of traditional house in Korea

Source: M-D. Park et al (1995)

2-3-1. Concept of the Formation of Housing Types

The design of the traditional folk houses was influenced by socio-cultural as well as climatic considerations. The main social concern is to maintain sufficient privacy of the house from the outside and to screen women inside the house. The primary climatic consideration is to provide comfortable indoor environment through site planning, space organization and use of proper building materials. The dominating idea of fengsui together with socio-cultural and physical constraints calls for developing the folk houses to adapt to their environment (N-C Joo, 1987). Such constraints are clearly manifested in the general concept of the houses as well as in the details of their component elements.

2-3-1-1. Physical constraints

1. Climatic factors

The degree of climate determining regional condition depends on its scale to which climatic variables respond. The severity and forcefulness of the climatic variables on a large scale firstly determine the regional climate conditions i.e. a macroclimate. Then a microclimate responding to specific local condition is arranged along the secondary climatic scale according to severity thereby generating the responses in terms of form, materials and building devices (Goulding et al, 1992). According to the general features described in the foregoing section, the climate of Korea is defined as being hot and warm-humid in summer, and cool and cold-dry in winter.

To meet with a long severe condition in the winter, the traditional houses are mainly oriented toward the south to obtain better availability and distribution of solar radiation. The angle of roof and eaves is also positioned to obstruct the high angle sun in summer and to catch the low angle sun in winter. Besides, the roof is designed to cope with heavy rains in the summer (J-O Koo, 1988). From the viewpoint of internal planning and layout, a plan having double back-to-back rooms which is likely to act as buffer zones to each other appears in the northern regions. On the other hand, a plan accommodating a wooden floor -Maru- is found in the southern region (N-C Joo, 1987; J-O Koo, 1988; K-H Lee, 1996).

2. Geological factors

Korea mainly consists of mountainous regions. Ranges of mountains pass through most regions in all directions, giving form to basins that contribute to creating their own cultural areas bounded on the mountains. As a consequence, the topographical pattern exerting a main influence over the climatic factors provides the background forming the specific local meso and micro-climate. Regions bounded on several mountains sides by display more distinctive local microclimates (Y-O Kim, 1985).

It has been suggested that vernacular builders always use materials most conveniently available, and that, since materials determine form, the nature of local materials determines form (Rapoport, 1969). Local materials together with sophisticated topographical pattern under the climatic conditions contribute to developing the diversity of floor plans of local traditional folk houses.

2-3-1-2. Socio-cultural constraints

1. Economics

Traditionally, main economic base has been agriculture, predominantly rice cultivation. As people became domiciled in their permanent dwellings, cultural forces from outside of their territory were less critical than physical forces thereby even less affected by sheer economic necessity (J-O Koo, 1988). Rapoport also points out that since people with similar economies may have different moral systems and world views, and since the house is an expression of the world view, economic life has no determining effect on house form.

Male family members mainly farmed upon their own land or tenanted a farm, whereas females are generally concerned with the management and maintenance of the household and occasional help in the field during harvest season. Accordingly a need raised to store away foods for the winter was met by producing a storage area in a plan arrangement. In addition, the introduction of livestock farming by the fact that every house on an average kept at least one cattle to sustain the needs of the family attributes its form to the need for man and animals to be close together (Y-H Kang, 1991). It therefore shows both concentrated and dispersed settlement patterns in a typical plan of a Korean farm with yard.

2. Religion

Folk belief that affects the form, plan, spatial arrangement and orientation of the house centres on the confucian idea and the fengshui theory. According to the Confucian idea, introduced from China, goodness and righteousness are the most important standards (Tang, 1997). As Confucians put a great emphasis on the idea of social hierarchy and order, the house form and device used were to be hierarchical in accordance with conceptual order. For the ancient Korean, the house is the temple for daily religion that leads to the separation of sacred and profane in plan.

In addition to the Confucian idea, the concept of the five elements, i.e. Fengshu order or Geomancy, also affected various aspects of ancient Korean life style. It was believed that rulers claimed legitimacy on grounds of heaven's approval for their success in war, and every ruler or ruling house reigned according to the sign of one of the five elements (Needham, 1978). In connection with the five elements, the ancient Korean has developed many architectural planning methods for house form associated with settlement pattern, landscape, direction of roads, water courses in the environment among the fortunate forms of trees and hills. For instance, it is preferable for a house to face low hills across water to the south and be surrounded by high hills to the north. Therefore, the house can catch the sun and avoid the wind in winter by means of utilising the slope and woods planted in rear hills.

3. Class divisions

As the ideas, such as the Confucian doctrine and the five elements, dominated over the ancient Korean in the Chosun era, a family's position was expressed by its socio-economic standing. The position was in the society where a member of the society could build his housing under restraints by rules and regulation on house size, material and decoration.

While the house belonging to the high style tradition varies in size and spatial arrangement, the folk house for the vernacular tradition that is much more closely related to the culture of the majority and life shows a less divergence in size and spatial arrangement to house form. It is due to the fact that adapting itself to the surrounding physical environment without the interference of any conceptual ideas has developed the Korean folk house. The unique Korean traditional heating system, Ondol, derived from a radiant heating system used in China has been found in the houses for both upper and lower classes through all the areas of Korea. But a wooden–floor, Maru, placed in housing plan for enhancing ventilation through openings has been applied to the housing plan only found in southern and middle parts of the country (J-O Koo, 1988).

2-3-2. House Form

In the period of the Chosun era, namely Chosun dynasty, there are three types of houses in Korea depending on the socio-economic status of inhabitant. The folk house, which consists of 2-4 rooms, a kitchen and a small court, was owned by low-class people engaged mainly in farming. Especially, floor plans in the folk house vary with local climatic conditions (Figure 2-6).

On the basis of this, the larger house of this type has an additional room on one side of the court and more affordable storage space by the side of entrance. With the characteristics of the built form embodying well its regional climate and natural environment, this type of the house can be considered the typical house of Korea. The main feature of the other two housing types for middle and upper-classes are summarised below.

House Type	**Main Feature**
Folk house	Common features shown on floor plan according to regional distribution
Middle-class house	Rather flexible methods shown on the type with larger plot
Upper-class house	The type having more than two blocks with various planning method

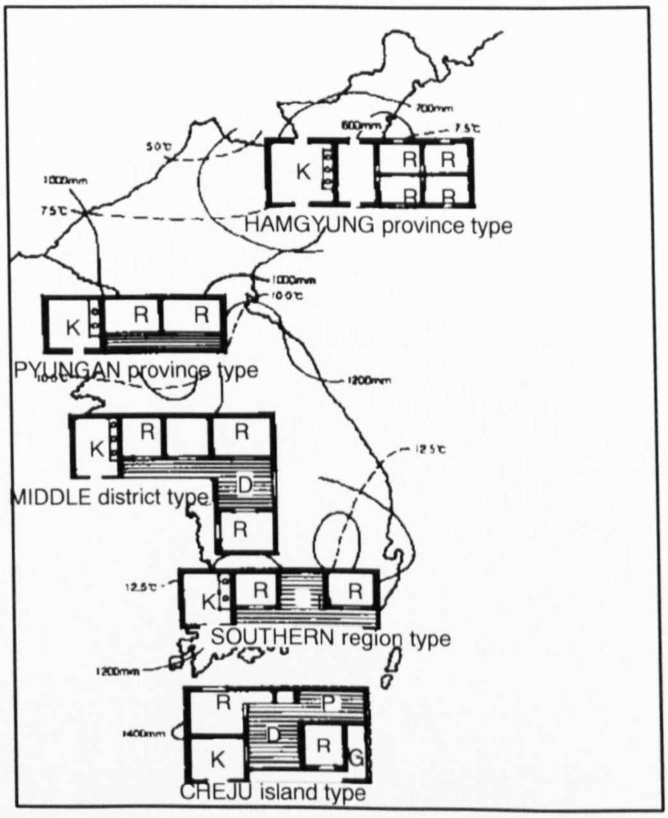


Figure 2-6. Floor plan of Korean traditional folk houses based on Joo's classification. (R) room; (K) kitchen; (D) Daechung (main wooden-floor room); (J) Jeongjugan (store); (P) Gopang (store); (G) Gulmok (fire house), and (C) Chuckdam (buffer space)

Source: N-C. Joo (1983); K-H. Lee (1996).

Among the three types of houses, it is believed that the folk houses were more easily inclined to adapt to the climate thus having evolved in response to the physical environment including weather and geographical conditions (Y-H Kang, 1991). The continuity of the influences from the physical environment on the folk houses are expressed in site planning, spatial arrangement, building materials and construction details within house structures.

1. Traditional folk housing type and physical environment

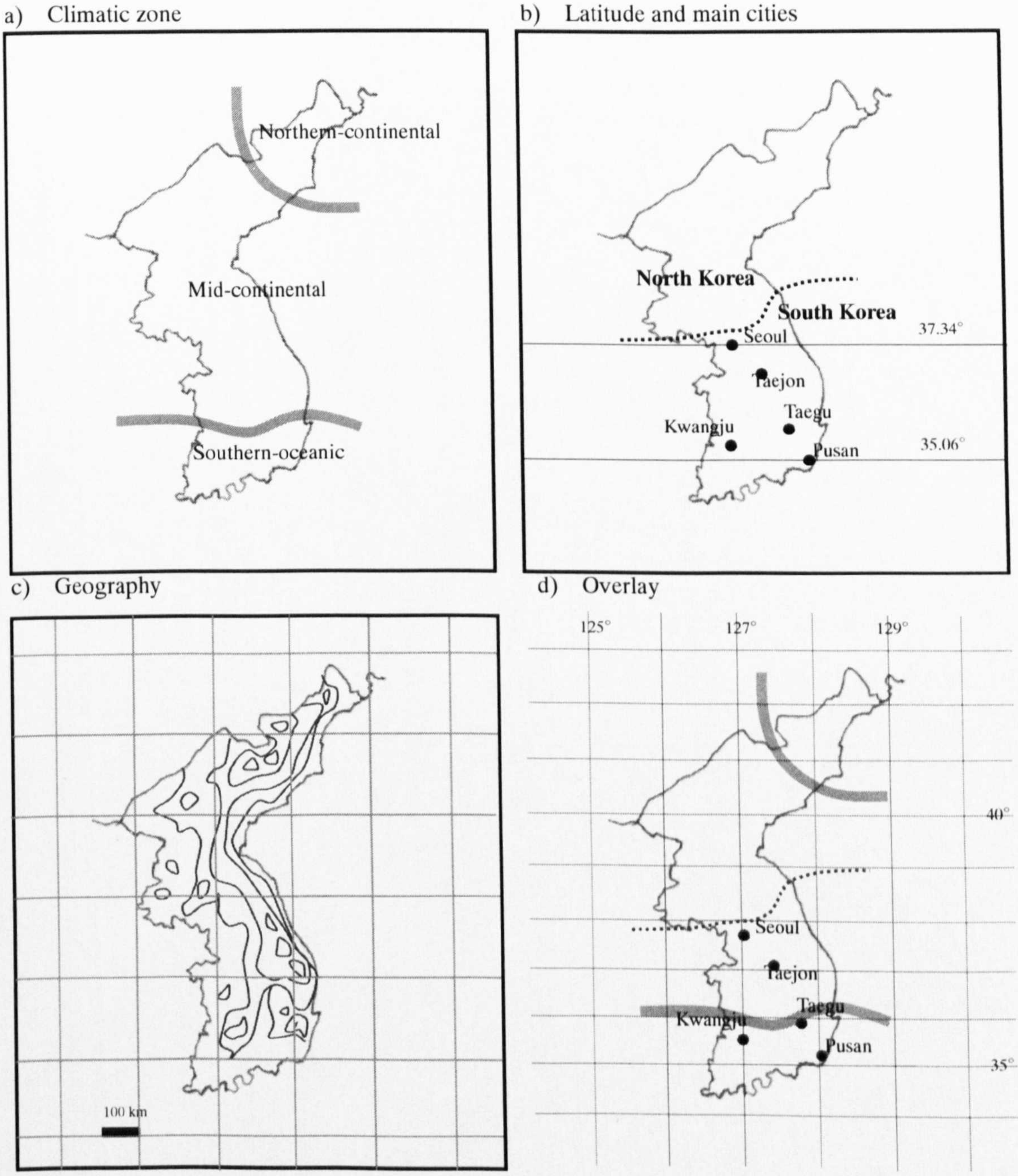


Figure 2-7. Housing type and physical environment in Korea

The climatic zones, as generalised in the previous section, can be grouped into three zones along with the geography pattern and administrative division of

Korea as shown in Figure 2-7. The administrative divisions of 8 sections cover six archetypes of the traditional folk house that shows unique floor plans in accordance with the physical environments of each division. In general, floor plans in the northern region show more complex and insulated style by adapting back to back rooms acting as a thermal buffer to block out the cold winds blowing and to keep the heat out. The Maru (Wooden floor) comprising floor plans of the middle and southern region appears due to the relatively mild and temperate climate. The features of the site and floor planning are arranged as follows.

(1) Northern continental zone

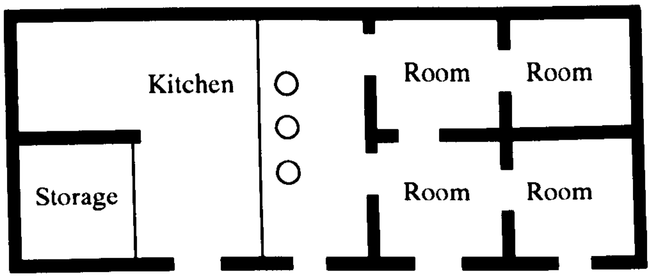
A double-crossed structure –double back to back rooms- found in the typical housing plan is one of the main characteristics of the folk house in the northern continental zone. The typical plan consists of four rooms, a kitchen and a multipurpose room (Jungjukan) in between. Other types found in the vicinity of the region show rather slight differences in the number and size of the rooms (Figure 2-8).

(2) Mid-continental zone

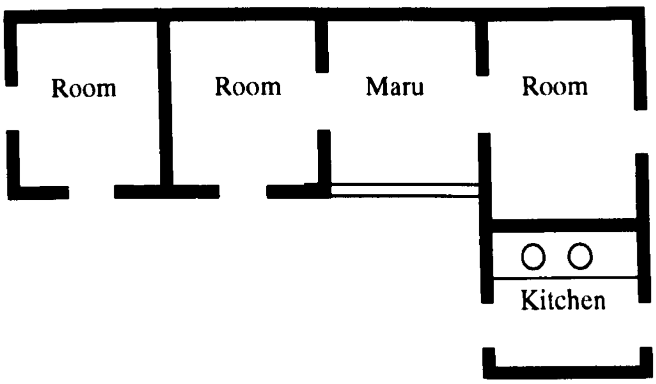
In the north-western and middle region, typical plans featuring an I and a L-shaped spatial arrangement built form including two rooms, a kitchen and a small wooden floor in front of the rooms are common. Courtyard structures with their unique compactness are formed in consequence of the combination of L-shaped and I-shaped block units. The combination further develops to centralised and semi-enclosed courtyard houses.

(3) Southern oceanic zone

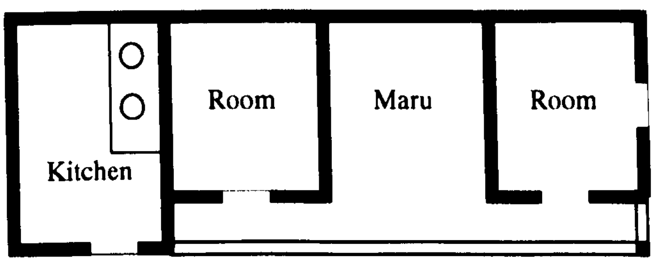
The types of the southern region adopt a spatial arrangement with more wooden floor space in plan that seems to be rather in common with the one in mid-continental region. The typical arrangement is formed of 2-3 rooms and a kitchen in its plan of rectangular shape.



(a) Type A: Northern continental zone



(b) Type B: Mid-continental zone



(c) Type C: Southern oceanic zone

Figure 2-8. Typical floor plan of according to climatic zone

Source: Y-H. Kang (1991); H-Y. Hong (1992); S-K. Cho (1996).

2. Enclosed housing plan and Linear housing type

There is a generally held view that a series of modification on housing form occurs when an area is acculturated to encounter other areas with a fairy different nature (Gavieta, 1991). The term, acculturation, can be applied to the mid-continental zone where two different types of housing form are derived from a form of opened and closed floor plan from southern and northern region are mixed with the influences of relatively temperate climate condition.

The first type of concentrated spatial arrangement –closed plan- is the indigenous folk house and it is found throughout the northern continental zone. In contrast, the second type is the plan of dispersed spatial arrangement –opened plan- in the southern oceanic zone. In the mid-continental zone, however, a courtyard was found as a result of the combination of L and I–shaped blocks, showing a series of modified form from the folk housing plan with its variations. (Figure 2-9) It seems particularly to be formed to neutralise the impact of the housing types from both the north and south zone.

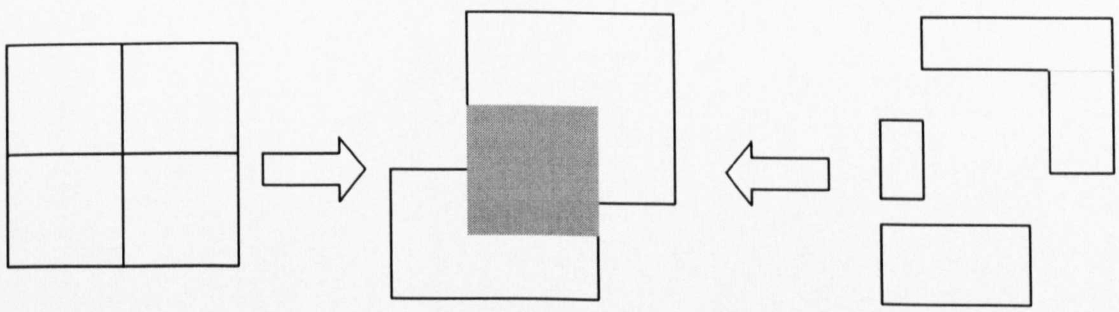


Figure 2-9. Development of courtyard housing type in the combination of enclosed and linear housing plan

The main design concept of the modified courtyard house is such that a housing plan consists of a collection of small and large courtyard spaces to obtain outdoor space in its building site. The small and large courtyards are for use to tackle the dense environment of urban areas by controlling air movement and sunshine penetration, further improving indoor conditions throughout the year. In general climatic influences in relation to the built form of the folk house are embodied in a way of composing the relationships of each unit in the floor plan of the modified courtyard housing form. The aspects of how the modified house conform to the urban environment and the site restraints along with the climatic influences are to be discussed in the following sections in detail.

2-3-3. Sun and Wind Control in Traditional Folk Houses

2-3-3-1. Passive control design features of housing plan

1. Northern continental zone

The dense spatial arrangement performs well for the long severe cold condition of winter. A buffer space called the 'Jungjukan is located between kitchen and room space in order to balance indoor temperature by preventing entry of strong wind from outside and keep temperature inside constant. A space for a use as barn and storage is placed with a kitchen side by side to further protect indoor temperature against local climate conditions.

2. Mid-continental zone

Houses with rectangular plan form the typical folk house in this zone. In many cases, the house is built around a court. Under urban environments where urban courtyard houses are found in the middle region, a courtyard as a design feature is adopted to let winds into the house. However, in winter when there is no special need for ventilation, windows are opened during the day and kept shut at night.

3. Southern oceanic zone

I-shaped blocks consisting of a folk house having one or two courts is common in this zone. It performs by controlling ventilation well under the humid climate. When temperature reaches its highest in the daytime, courts placed around a main housing block enhance cross-ventilation through main wooden-floor room. Natural convection developed by cool air movement through the wooden-floor leads to lower indoor temperature even in hot summers.

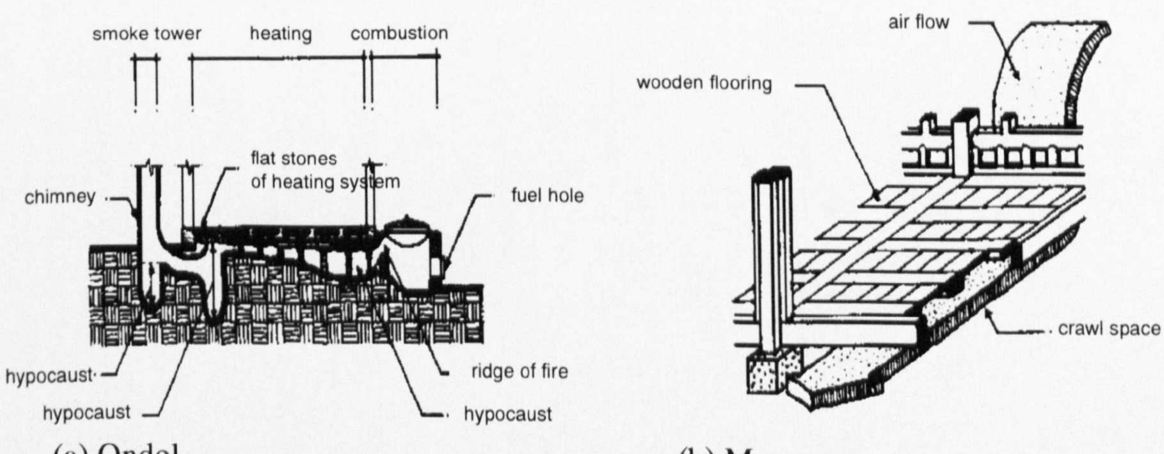
2-3-3-2. Passive design features of heating and cooling systems

1. Mud-plastered inner and outer envelope

Layers of mud plaster on walls are commonly applied to wall and roof. A layered thatched roof structure is then finished with clay tiles (Y-O. Kim, 1996). In the summer, the wall and roof act as insulating elements to keep the heat out. In the winter, solar radiation penetrating into indoor spaces is absorbed during the day and cools down with a large time lag to create a warmer indoor environment.

2. Wooden-floor living room: Maru

The flooring method of panelling wooden materials provides a good way of controlling indoor environment in the middle and southern region. The floor is built elevated about 40-50cm above the ground level. In summer, the airflow under the floor makes ambient air cool by intercepting direct sunlight, controlling the humidity and penetrating through peepholes of the wooden-floor room where activities take place (K-H. Lee, 1996).



(a) Ondol (b) Maru

Figure 2-10. Sections of heating system 'Ondol' and ventilating system 'Maru system'

Source: K-H. Lee et al (1996).

3. Hypocaust: Ondol

Korean under floor heating system is used in the inner room of the folk house for the heating season. The Ondol is a system of layers of gravel placed on the bare ground. Then large stone slabs are placed and clay is plastered above it. As a finishing layer, the flooring material is of paper, which has been oil treated. It is the system of controlling the humidity, heating and natural cooling effect by adopting radiant heating method as the surface temperature of the system reaches up to 25-50°C, achieving comfortable environment during the winter (Y-O. Kim, 1996).

2-3-4. Schemes on Morphology of Housing Form

In general, there are two ways of classifying the housing plan according to its architectural characteristics. The first method is to define the housing plan by its relation to the surrounding physical environment, depending on the climatic condition and geographical pattern. Under the category of this method are the schemes of Iwaki Yoshiyuki, Nomura Takehumi, Y-T Lee, K-U Jeoung, J-K Kim and N-C Joo. The second is to categorise the plan on the basis of its spatial arrangement regardless of the influences of the surrounding environment. The work of B-U Jang, H-S Kim, J-M Lee, K-E Kim and Y-H Shin belongs to the category of this second method (K-U. Kim, 1988; H-O. Hong, 1992).

2-3-4-1. Schemes in relation to physical environment

Several attempts to apply the schemes on the morphology of the folk houses have been made in the light of mutual influences between the housing plan and its surrounding environments. They lay special emphasis on three fundamental indoor spaces, i.e. kitchen, room and Maru (main wooden floor room), by way of most sensitive spaces to their regional microclimate (N-C. Joo, 1980).

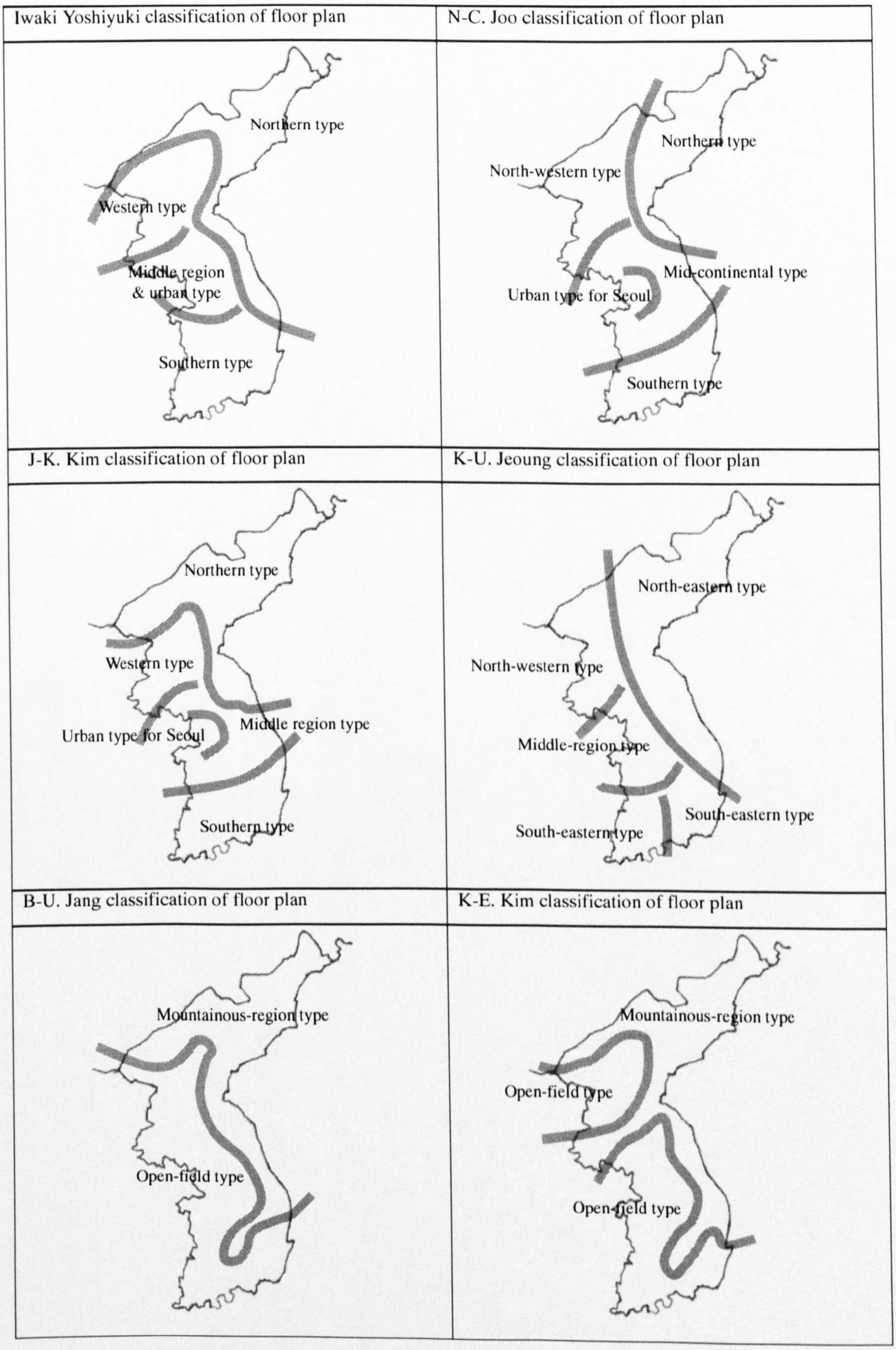


Figure 2-11. Floor plan classification suggested by the schemes

An initial suggestion of ways of classifying the folk houses refers to a scheme of the housing plan by providing five prototypes of the plans, namely, the housing type for the northern, southern, western, middle area and Seoul (Yoshiyuki, 1924). In fairly general terms, his scheme is mainly on the basis of the presence of a living room in the housing plan in each climate zone.

Takahumi (1938) tends to list the principles of the housing types concerning both the characteristics of built form in southern oceanic island zone – Cheju Island- and geometrical properties of the double back to back rooms found in the northern continental zone. As classifying the housing types into four basic types, the types for island, northern and urban area in addition to a general type, he also points out that the planning layout of the houses, double back-to back rooms, found both in the northern and island zone holds spatial arrangement in common. Regardless of a wide climatic differences between both zones, a modification has to be suggested to his scheme on how to categorise the types of housing plan located inland in further detail.

K-U Jeoung (1972) described that the courtyard-style house in the urban area, Seoul, introduces both wooden floors derived from the southern region and planning layouts from the south-western region, combining both influences into the plan under the urban circumstances.

In the study of the history of Korean housing, J-K Kim (1970) considered housing types being classified into northern, southern, middle and south-western type further including urban and island types. His aim is to suggest a general form in close connection with its microclimate from the broad viewpoint. He summarised the folk housing types as; Urban type for Seoul, Northern type, Western type, Middle region type, southern type and Cheju Island type.

A study has been directed towards investigations on the relationship between the yearly mean temperature and the housing floor plan of the regions (N-C Joo, 1972). Housing types are divided into six types; i.e. northern, north-western, mid-continental, urban, southern and island type. While considering all the schemes of the folk housing types in more systematic ways, he stressed that there were close connections between the physical environment and housing types by displaying the regular distribution patterns of the housing types.

2-3-4-2. Schemes in relation to spatial arrangement

In the field of study on the classification of the housing types, a number of studies have been presented for the schemes in the light of spatial arrangement. Regarding the spatial arrangement of a type of the housing plan, two types of the plan -open and closed plan- have provided for the bases of the classification. The definition on how to name the two types of the plan to be classified vary according to the purpose of the studies.

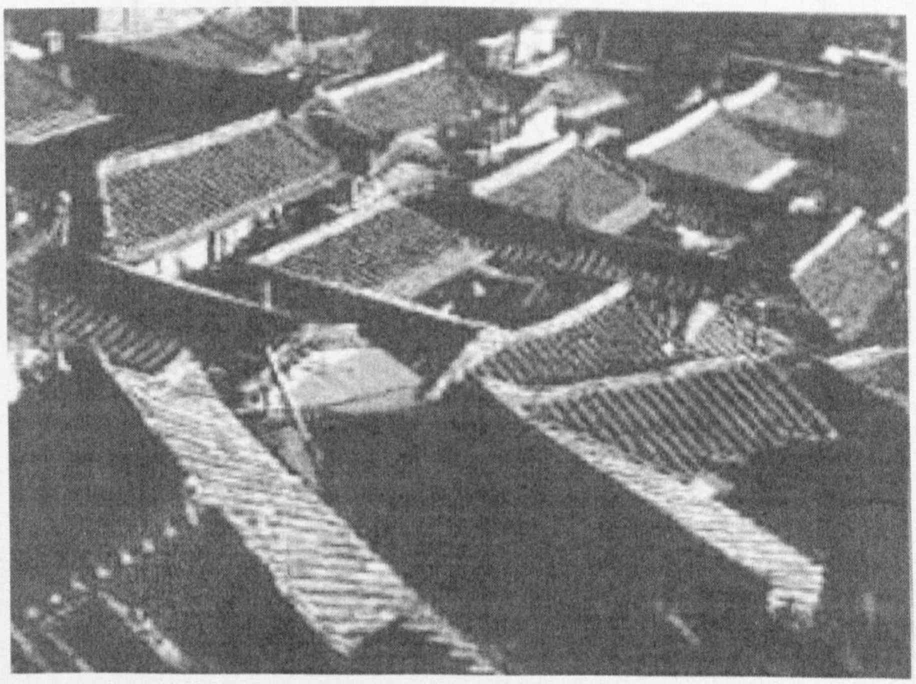


Figure 2-12. Typical view of the semi-enclosed courtyard house of an urban area built during 1930-60

Source: The Architectural Institute of Korea (1999).

B-U Jang (1974, 1980) in his study of the classification method of floor plan types of Korean folk houses reveals that the open type of housing plan has a great advantage in hot-humid and cold climate owing to its relatively good performance in controlling solar radiation and humidity. The study has shown a distribution chart in which a distribution range of three types of the housing plan (types for a mountainous region, an open field and an Island) is represented.

Investigation undertaken by K-E Kim (1988) has shown the a range of the closed types of housing plan reaching to further southeastern parts of Korea. It is seen that the semi-open type of housing plan found in the southeastern region tends to be categorised into the closed type taking established detailed knowledge on a microclimate conditions indicated in the specific part into consideration.

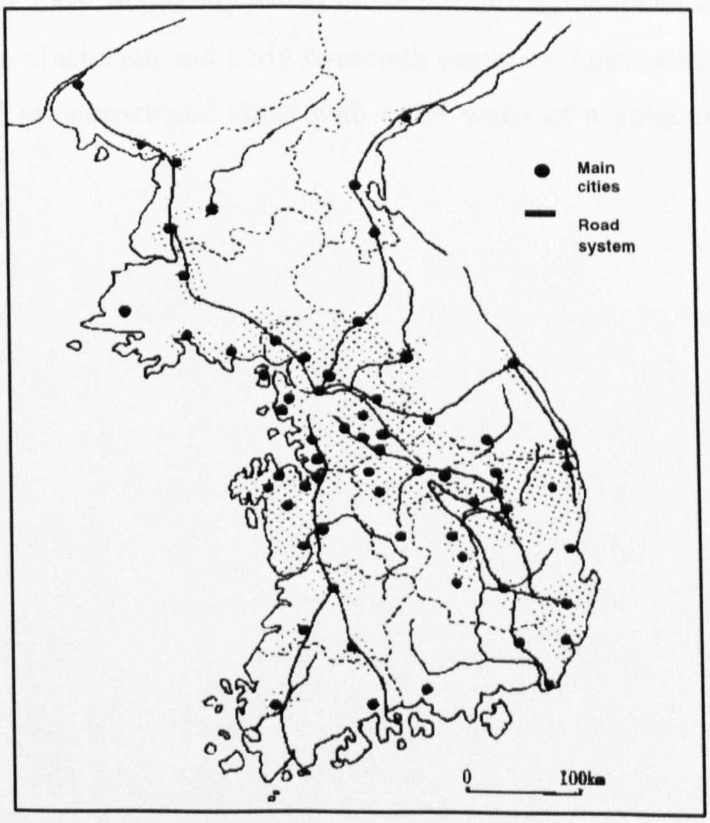


Figure 2-13. Regional distributions of courtyard houses

Source: H-O. Hong (1992).

A series of studies concerning the housing types and their distribution pattern also contain numerous studies that have been done in the field of a courtyard housing form. The knowledge obtained from the studies is of good use in understanding the relationship between the physical influences and the courtyard housing form in the urban environment.

With regard to the geometrical properties of courtyard housing form, it is clear that the courtyard housing form that consists of courts and surrounding housing blocks ensures an open inward looking nature for every dwelling and isolation from the outside world. In Korea, studies on the courtyard housing form have indicated that the application of the courtyard into the folk housing form was to imitate the housing form for the upper classes or to secure the privacy of the family from outside (Hong, 1992; Park, 1996). The plans of the courtyard houses, which are most frequently found in the middle region including the capital, Seoul, in the late nineteenth and early twentieth centuries, show a series of blocks around a closed or semi-closed court with outer walls of a number of windows (Figure 2-13).

2-4. Courtyard House: A form for urban context

2-4-1. General Overview on Courtyard Form

From the viewpoint of energy-conscious tradition, the courtyard house form provides heat, light, ventilation and other functions to buildings which surround it. Its structure, size and shape play an important role in modifying climate (Bensalem, 1991). Dennis Ho (1996) points out that, apart from acting as climate modifiers to meet the needs of occupants for thermal comfort, the courtyard house form can provide spatial and visual amenities to otherwise monotonous deep plan buildings. Numerous examples of the courtyard house form in planning and building design related to climatic condition are found in high-density urban environment throughout the world.

In the absence of modern building technology, builders, who mostly did business on their own account, in several towns of Seoul from 1900–1960, have developed urban areas in creating an unique environment that is in tune with nature and urban structure. The urban housing development including road system and block layout not only provides for the basic needs of the occupants but has distinctive features in its background in forming urban courtyard housing that is distinguished from the other types of the folk houses discussed in the previous section. The aims of this section of the thesis are firstly to determine what these features are, secondly to find how the features are interrelated in the process of settling in the towns. Therefore it is to suggest the underlying principles of the urban courtyard housing in the light of the urban housing structure.

To summarise the features of the urban courtyard housing, this section is conducted at two levels;

1. Urban structure: patterns, site and plot dimension.
2. Housing form: orientation and shape.

2-4-2. Urban Housing Structure

2-4-2-1. Basic concept of urban structure

1. Urban spatial form

An urban spatial form of the patterns of street and block layout constitutes a network which has an influence on a regional house design including its form, shape and orientation. Different urban spatial forms may have different characteristics. Alexander (1966) points out that, as a formal pattern such as a semi-grid and a grid can be much more complex than an informal pattern, a tree, because a semi-lattice allows a far greater number of linkages than a tree (Figure 2-14). He also made a comparison on two simple, contrasting patterns, which is characterised as follows;

Issue	Tree	Grid
Movement:	segregation	shared street
Traffic:	concentrate	disperse
Land use:	zoned	mixed
Street pattern:	enclaves	connectivity

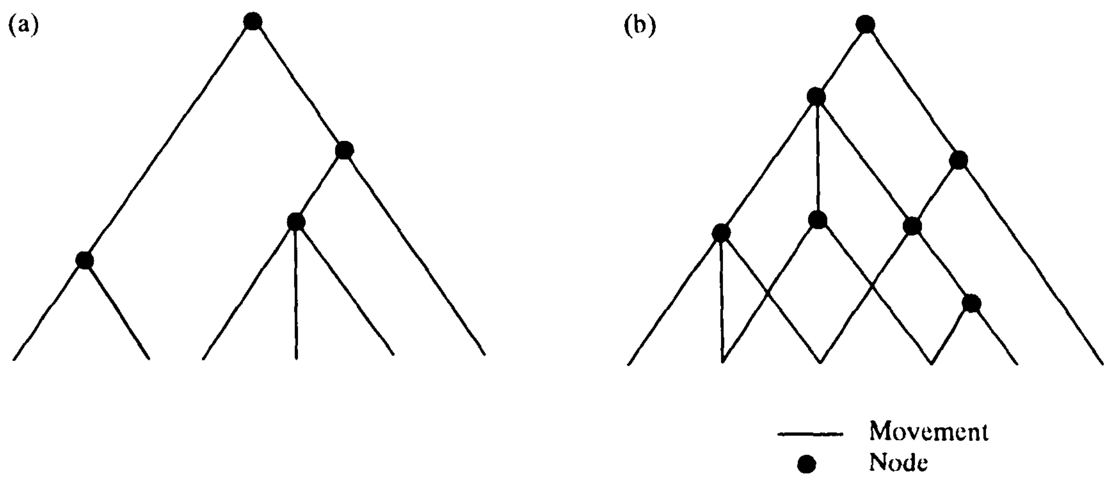
In order to establish the criteria for this examination of the spatial variations, it is necessary to consider urban forms by conceptualising the pattern, i.e. Informal and Formal pattern.

(1) Informal pattern; Tree

The characteristic of the informal pattern is to dispense with some of the direct connections between place and origin and to connect these places to the remaining radial paths. The typical informal pattern has some advantages that all the junctions can be made suitably simple. A feature of the informal pattern is that it produces a series of dead ends, inhibiting free-flowing movement through the area.

(2) Formal pattern; Grid

A grid arrangement of the patterns offers more direct routes between places than is possible with a tree pattern. A disadvantage of a regular grid of this type in the context of access is the junction of a large number of paths at the same node. But a grid pattern has the useful property of providing equal coverage over its whole area. Each site is easily altered to provide for changing conditions.



(a) 'Tree' showing separate elements (b) 'Semi-grid pattern' showing overlapping elements

Figure 2-14. Concept of 'Tree' showing separated elements and 'Semi-grid' showing overlapping elements

Source: Christopher Alexander (1966).

2. Site

The majority of courtyard housing forms is found in the mid-continental zone in which the housing forms, hybrid forms of the open and the closed housing plan, are produced as a result of climatic modifications. Therefore, Seoul, the largest and capital city, situated in the mid-continental zone where more than one-fifth of population has been concentrated, is chosen for this study, providing an opportunity of examining changed phases of urban morphology. As Seoul is one of the oldest cities with historic architecture dating from 1394, city planning needs to be examined from each historical period and its own concepts of urbanisation and building design, some were unique and others were adapted from period to period.

The urban geometry of the city has undergone enormous physical changes from 1900's as there have been new developments in historic settlements and architecture. It is noteworthy pointing out that the urban spatial form became transformed from the tree pattern to the grid pattern during these periods (I-H. Song, 1990). It is expected that findings from the analysis of the selected town plans will lead to compiled data for the next chapter, providing the most important design principles that have been displayed on the pattern and configuration of the town plan with its evolution.

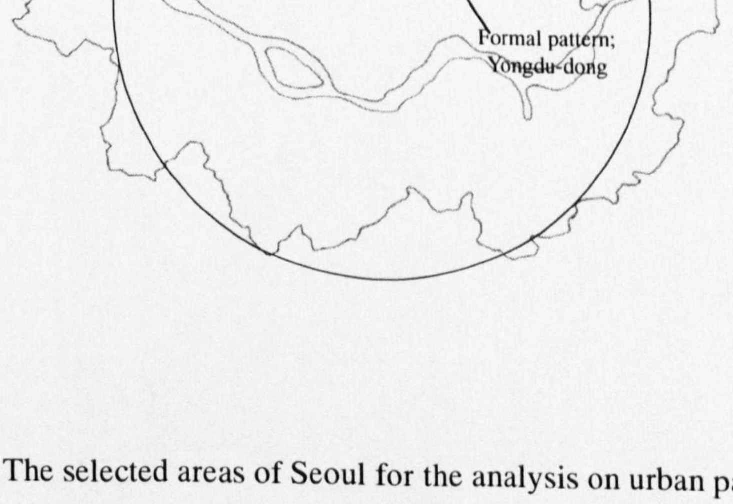
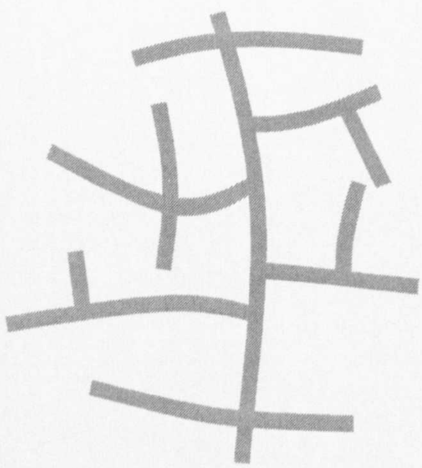


Figure 2-15. The selected areas of Seoul for the analysis on urban pattern

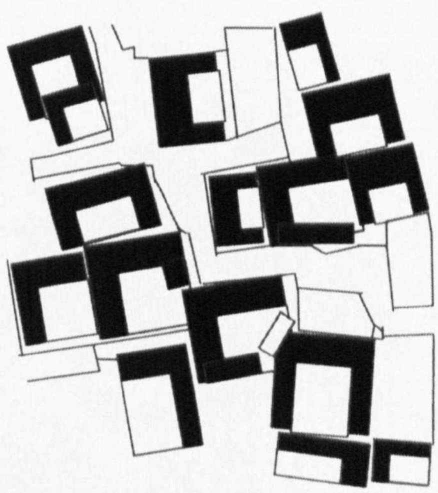
2-4-2-2. Town layout

To find out the typical changes of the town pattern, firstly, examples of the irregular patterns, i.e. tree pattern, appeared in towns located around city centre are given. Secondly, transitional patterns placed between the tree and the grid pattern are expressed. Thirdly, the regular patterns mainly found in the vicinity of the city centre are represented. Approaches to the investigation of the ranges of the town plans will help define the main features of urban courtyard housing whose pattern derived from the road direction and block layout of a town is the most important element that has direct relation to the sustainability of environment.

1. Informal pattern



(a) Image



(b) Existing street pattern: Anguk Dong

Figure 2-16. Street layout of typical informal pattern

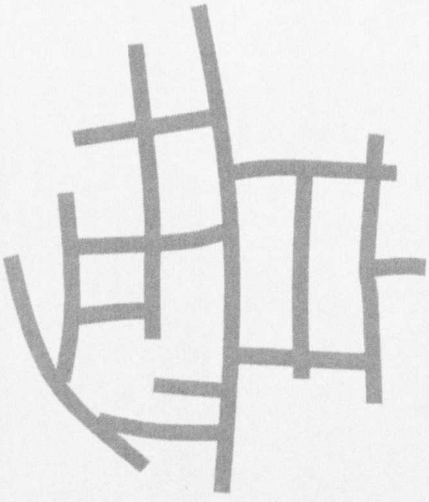
Source: J-Y. Park (1996).

The informal tree pattern, which is believed to be the form of the earliest stage for urban development for town layout, can be found in areas close to the centre of Seoul. As the tree pattern can not be considered as a deliberately planned layout, it results in generating several types of blind alley. Figure 2-16 illustrates enlarged and simplified examples of the areas with the informal pattern.

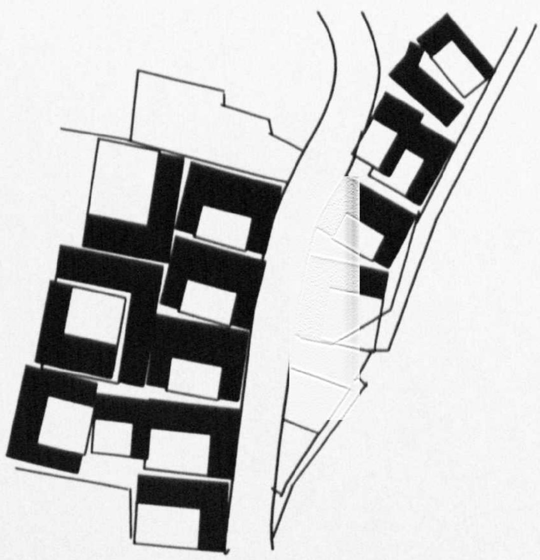
The E-W streets are about half the width of the main N-S streets, being less exposed to the sun. Dwellings are mostly one or two stories high, and with one or more internal courtyards for obtaining privacy and creating desirable indoor climate (I-H. Song, 1990; Y-H. Kang, 1991; J-Y. Park, 1996). From the available images, it can be seen that the pattern of the orientation of the courtyards mainly faces towards the south or east. Therefore the selection of the sites for each dwelling depends on how to orientate main access and the street, having good relationships between two.

2. Transitional pattern

By introducing the planned housing complex built into a rather irregular street pattern, a series of semi-closed courtyard houses is created in a more organised manner, showing a regular type repetitively formed.



(a) Image



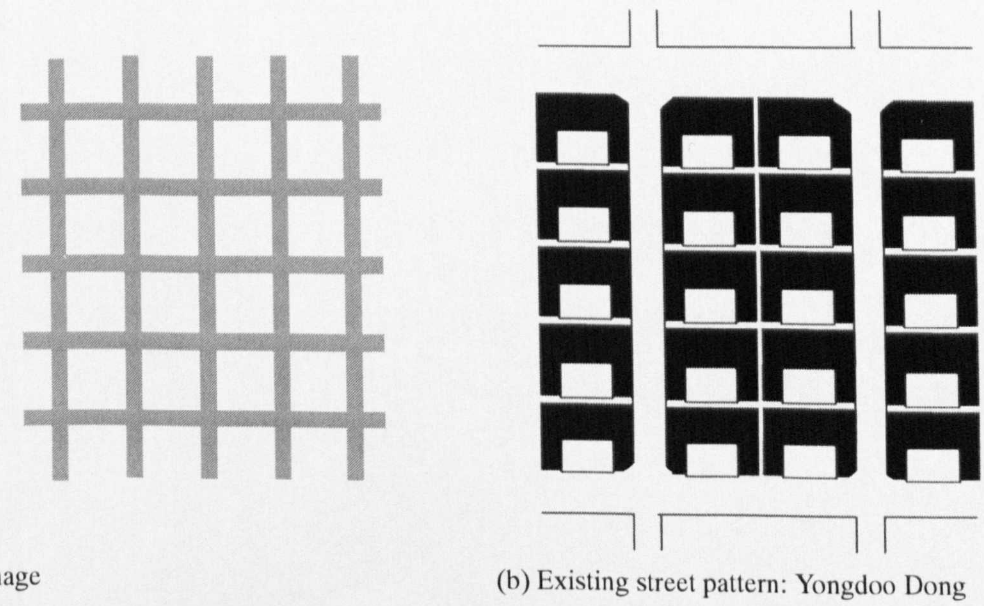
(b) Existing street pattern: Kwonnong Dong

Figure 2-17. Street layout of typical transitional pattern
Source: J-Y. Park (1996).

As shown in examples of Figure 2-17, there are less hierarchies for the relationships between the main and minor streets than those of the informal pattern from the viewpoint of street width and direction. These communities of the transitional pattern are planned on the principles of giving precedence to planning each site for dwelling over organising the street system. Namely the area was parcelled out into small sites in consideration of gaining good access from the street to each site, indicating the pattern development on the basis of spontaneous growth (I-H. Song, 1990; J-Y. Park, 1996). For the both communities shown as example, urban layouts of gaining access from east and west are mainly found while securing privacy inside of the dwellings is achieved by means of having highly formal closing walls facing the street.

3. Formal pattern

As a typical feature of formal grid pattern, which is mainly found in the vicinity of the urban centre, the direction of most streets is so systematically organised that it is difficult to classify the hierarchy of the streets in order (Figure 2-18). The apparent features and images indicate that the pattern of urban layout has been remarkably advanced and modified



(a) Image (b) Existing street pattern: Yongdoo Dong

Figure 2-18. Street layout of typical formal pattern

Source: I-H. Song (1990).

It is interesting to point out that a way of systematic approaches is embodied in the town planning as the planners and the occupants seems to aware of the need to share even planning condition for each dwelling. A typical courtyard house of grid urban layout is in harmony with the strict formal pattern by simply duplicating its own prototype.

2-4-2-3. Housing plot

1. Housing density

A process of dividing the site of development and deciding the dimension of the plot for houses is a function of the town norms of the street system. The foregoing examples on the town plans provide an indication of this. A plot for larger size can be obtained in proportion to the dimension of a town plan. In principle, it is recommended that good conditions for obtaining optimum urban layout planning can be achieved at densities of 25-35dph (Yannas, 1994). However, the average built density of the traditional town plans in Seoul is about 75-80 housing units per hectare (dph). The constraints on the densities of traditional town layout planning may be caused from socio-economic and physical consideration as discussed in foregoing section. Urban sites require special attention to density through housing form, roads and dwelling access.

On average, the town with a tree pattern consists of larger plot size, indicating around 55 dph that marks quite low density compared to housing density of up to 72 - 97 dph developed in examples of the grid pattern which is mainly found in the vicinity of the urban centre. This seems due to the fact that the towns of informal pattern were built in the early years and were less exposed to the constraints. Thus the denser development could be achieved in a form of formal pattern, i.e. grid pattern, of the town site layout of Seoul and there may be more opportunities for dense clustering of housing through town planning design by introducing an efficient pattern strategy in land use.

Figure 2-19. A layout of urban courtyard housings illustrating densely built pattern

Source: The Architectural Institute of Korea (1999).

2. Plot - shape and proportion

The implication for the relationship between plot frontage and width will vary as a function of frontage in proportion to width in terms of road access and orientation. I-H. Song (1992) has defined a typical plot of the town planning of Korea as a plot with its shorter side to the road than other sides at right angles and its longer side to the south (Table 2-7). For a given size, widening a plot frontage to the south results in reducing its width. Arrangements for individual rooms for the courtyard houses can then be considered in relation to the orientation of access to the houses.

Some common features involving such site conditions in the town planning of Seoul are summarised below.

① Courtyard, an important architectural element, accommodated in town housing form and layout under consideration of privacy and security aspects.

② Orientation towards to south with respect to room functions by siting houses with a western or eastern entry close to the road.

Table 2-7. Percentage of housing plot by plot proportions

Plot distribution by ratio of plot depth (D_1) to plot width facing to front street (W_1)		Plot distribution by ratio of plot depth (D_2) to plot width facing to due south (W_2)	
Ratio (D_1/W_1)	Percentage (%)	Ratio (D_2/W_2)	Percentage (%)
0.9	9	0.6	9
1.0	12	0.7	10
1.1	17	0.8	23
1.2	10	0.9	15
1.3	14	1.0	10
1.4	6	1.1	16
1.5	4	1.2	3
Others	28	Others	14
Total	100	Total	100

Source: I-H. Song (1992).

2-4-3. Courtyard House Form

2-4-3-1. Design principles

1. Zoning of typical housing plan

As discussed in section 2-3-2, common housing types in the mid-continental region are found as combined housing shapes of an L-shaped block unit and an I-shaped unit. The typical zoning is presented on the basis of placing kitchen at the end of the left wing, and having a row of room and living room (Maru) in front of the main unit of the house. As opened or closed as a result of combining the block units, the courtyard form leads to the urban courtyard house in a compact-planning layout (H-O Hong, 1992).

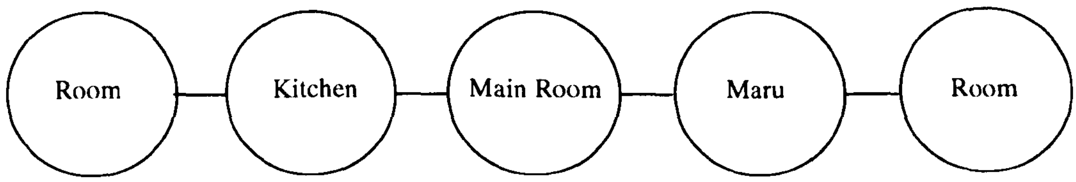


Figure 2-20. Typical Zonings of L-shaped houses

Source: H-O. Hong (1992) & J-Y. Park (1996).

Generally, in the case of the urban courtyard housing types, the traditional placement of individual rooms is by kitchen, master bedroom, living room (Maru) and bedrooms in order, which derives its planning and layout from the zoning of L-shaped house form of the mid-continental region. It is also the general rule that, in most cases, the orientation of kitchen faces to main entrance (J-Y. Park, 1996). The relative positions of the individual room on account of the orientation of the main entrance in turn yield a general principle on house planning and layout.

2. Design development

Processes for the development of typical housing planning and design are characterised by the concepts of flexibility and adaptability (De Chiara, 1984).

In Korean urban housing, the concepts can be applied and reinterpreted that,
① Flexibility is an important consideration in establishing planning and design stages for the L-shaped housing form as an initial process before the development of the U-shaped housing form.
② Adaptability is another reflection of the design development of the U-shaped urban housing form on a compact plot with urban constraints that have to be accepted.

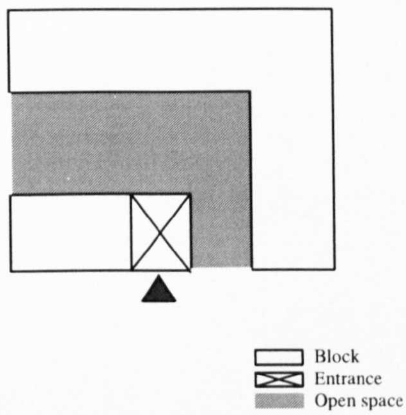
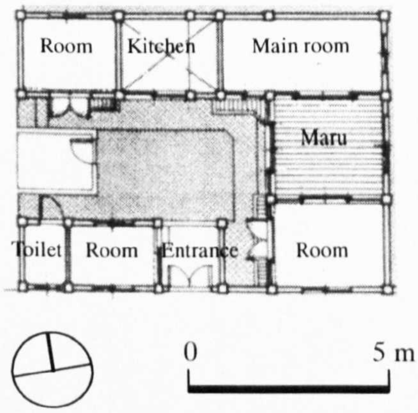
The U-shaped forms of a courtyard house are differentiated by two geometric parameters: the number of storeys (building height) and the degree of detachment (building and plot dimension), which are to be used as housing layout factors in a later section. The degree of detachment of the forms affects the pattern of the town-housing layout including road system, courtyard's geometry and orientation. The number of storeys affects the level of density of households in urban sites. Overall, the parameters relating to a courtyard housing form in the town of urban centre are determined by a series of site conditions that dictate site densities and orientations. Processes for determining courtyard housing types and sizes resulting from urban constraints are discussed in more detail in the following.

2-4-3-2. Courtyard housing type

1. Semi-opened courtyard house

The semi-opened courtyard housing shape arise from diverse adaptations of housing design from L-shaped housing forms of the mid-continental region. This type of house has some flexibility to the plots of the urban site by modifying the plan layout.

There are some detachments in the generalised plan of semi-opened courtyard houses; it is largely a function of a degree of combination of the L-shaped and I-shaped block. The difference of the height of two blocks also attributes to the degree of detachment of the roof. In addition, the siting of the entrance space is another factor, which is dependent on the shape of housing form, for classifying the semi-opened and the enclosed courtyard housing shape. Unlike the enclosed courtyard house, it is rare for the semi-opened courtyard house to accommodate entrance spaces within planning layout (I-H. Song, 1990). Therefore, the development of the housing plan layout on the basis of the flexible adaptation of those architectural elements can be explained especially for a link between the semi-opened courtyard house and the enclosed courtyard house.

Semi-opened Courtyard House	
Generalised plan layout	Example
	

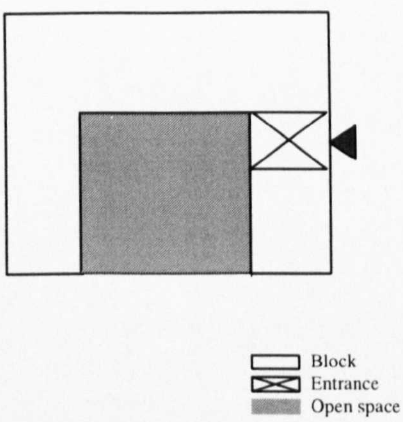
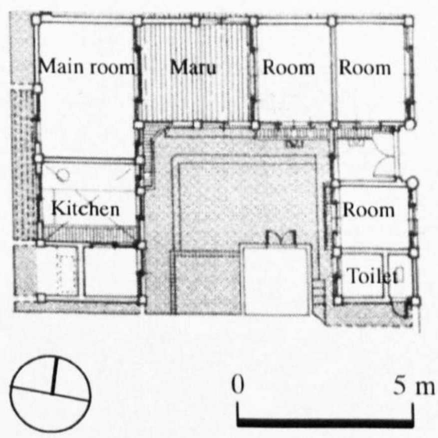
Enclosed Courtyard House	
Generalised plan layout	Example
	

Figure 2-21. Comparison of housing plan of semi-opened and enclosed courtyard forms

Source: I-H. Song (1990).

2. Enclosed courtyard house

In the enclosed courtyard house type, Each block of the house is rigidly combined in a U-shaped form, presenting a complete plan layout without disconnection of housing plan layout (Figure 2-21). The compact housing type appears to have been influenced by an urban constraint under which a series of spaces for entrance and service are housed in the end of the courtyard house as a complete unit (I-H. Song, 1990; J-Y. Park, 1996). To sum up, the development of the courtyard housing plan together with the unique planing layout and housing form provides a sort of prototype of the house design for urban sites.

3. Multi-story courtyard house

These types of multi-storey courtyard housings, which is characterised by a series of U-shaped forms, were introduced to make efficient use of urban sites. However, traditional spatial characteristics of a semi-enclosed courtyard house remain unchanged. As referred in section 2-4-2-2, the dense clustering of the semi-enclosed courtyard house on a regular base of the gird pattern forms implies a modernised concept for typical urban housing types.

Summary of the Chapter

In this study, an analytic approach to climatic conditions and traditional courtyard houses of Korea has led to the following remarks.

The climatic zones of Korea defined by those schemes from the macro-climatic viewpoints indicate three types of climate conditions; Northern continental zone (cold winter and mild summer), Mid-continental zone (cool winter, mild summer) and Southern oceanic zone (mild winter, hot summer). In general, bioclimatic analyses show that the summer season lasts from June to August being hot and humid, and the winter season from November to January characterised by severe cold and dry period. It seems clear that the geographical pattern of Korea together with climatic patterns plays an important role in dividing the climatic zones and, consequently, providing a series of distinctive regional traditional housing plans according to physical environments..

With physical and socio-cultural constraints, various types of traditional folk houses appeared with unique systems such as Maru (for enhancing ventilation) and Ondol (for inducing effective heat). Of the housing types, semi-opened or enclosed-courtyard housing plans, commonly found in the mid-continental zone, have been developed to meet the needs of housing people in cities at high densities of population. The urban courtyard house has remarkable features in the formation of urban town planning and housing design by demonstrating relatively high level of land-utilisation as well as providing comfort. Seoul, the capital city, situated in the mid-continental zone is chosen to study the patterns of the town planning during urbanisation.

At the level of the urban town planning, the pattern of planning has undergone remarkable changes from informal to formal pattern via transitional processes. The formal pattern has become the more dominant feature as urban developments proceeded. In many cases, a plot side facing to the south is slightly longer than the other side of the plot. At the level of courtyard housing plan design, prior to giving form to semi-opened and enclosed courtyard house, most of the housing form consists of I-shaped and L-shaped blocks. Therefore, to adapt its plan to a compact urban plot of housing developments, each block unit has become unified, showing a completely enclosed U-shaped form.

Chapter 3

A Model for Passive Solar Courtyard Housing Layout

3-1. Introduction

In urban housing developments, density policy appears to be an important element since it plays a significant role in ensuring adequate spacing in housing layout to avoid overshadowing on blocks. The issue of density and solar access has been dealt in elsewhere (Ó Catháin, 1977, 1978, 1981; De Chiara, 1984; J.T Kim, 1997; Pitts et al, 1997; Cadima, 2000). The studies on these issue indicate that, in order to set out a coherent density policy for solar energy in relation to housing design, the interactions of the variables involving housing layout geometry and solar energy criteria must be understood. It therefore is said that land use policy is closely related to solar energy available to a house within certain plot conditions

.

The aim of this chapter is to develop a series of density expressions in terms of identifying solar energy availability within a range of courtyard's geometrical shapes by introducing site planning and housing layout factors. Those factors therefore impinge upon plot size, dimension and courtyard spacing, based on a theoretical model of housing layout with special reference to traditional urban courtyard housing. It is also noteworthy that Korean building regulations applicable to residential areas have an influence on the scope of usable courtyard areas according to plot's size and dimension.

In this context, this study is carried out by,

1. Deriving the housing layout factors, defined as ①Plot size, ②Plot dimension, ③Number of housing units and ④Housing orientation in relation to the total number of stories; all of which influence a variation of the usable courtyard space.
2. Parametric analysis performed to compare the relative importance of the factors on the relationship between a range of courtyard spacings, dimensions and their corresponding solar radiation, and to find out the scope of the optimum shapes of courtyard housing in relation to each housing layout factor.

By examining the relative scope of solar energy availability quantitatively, and by considering a series of courtyard sizes and dimensions classified on the basis of identifying the relationship between the factors, it is intended to state optimum values for parameters of housing layout factors which are more beneficial to ensure relatively sufficient sunlight entry into the courtyards. In order to investigate the relative importance of the housing layout factors, the parametric and comparative analyses are divided into two stages.

1. The building regulations that particularly relate to housing layout density are reviewed. This study examines the selected sections of the building regulation codes related to ①Building size ②Density standards per unit area and ③External space standards in terms of land-utilisation.
2. A series of theoretical layouts of courtyard housing in urban development is modelled to derive an expression for usable courtyard space in terms of the housing layout factors. The variation of the usable courtyard space is investigated by applying the housing layout factors.

3-2. Planning and Design Policies: regulatory criteria

The term, "housing", is defined in the Korean Building Regulations for housing development promotion (Article 3, clause 3) as a building inclusive of its plot or a part of a building that provides living space for a household for a long period of time. In a broad sense, according to the provisions of the regulation, there are two types of housing, detached houses and flats. The former is a type of house to accommodate a single family in principle and the latter is a type of stacked up housing unit that are subdivided into a type of apartment building, attached house type I and attached house type II. The classification and definition of housing types as outlined in the building regulation is briefly summarised in Table 3-1.

Table 3-1. Range of housing types: Code for housing development promotion (Article 3, clause 3)

Housing type		Remarks
House- detached	Detached house- Type I	for single family
	Detached house- type II	for two or more families; less than 3 stories & building area under 330 m^2
	Detached house- type III	for two or more families; less than 3 stories & building area under 660 m^2
	Official residence	
Block of Flats	Apartment building	Block of flats with more than 5 stories
	Attached house-type I	Block of flats with less than 4 stories: building area exceeding 660 m^2
	Attached house-type II	Block of flats with less than 4 stories: building area of 660 m^2 or less

This section of the study mainly focuses on describing the definition and classification of those issues related to housing development for single family houses based on the relevant articles, clauses and ordinances of the building regulations. This is to set up a geometrical expression of housing layout between density, courtyard spacing and solar access. As a courtyard house for single family in this study is categorised into the detached houses defined in the regulations, the sections of the regulations relating to the density of detached house are only dealt on the basis of standards on indoor and outdoor spaces such as building size and allocated community area (Table 3-2).

There are various regulations covering from urban planning to housing design which are applicable to the whole architectural process. Among the building regulations, the Code of Architecture, the main building regulation, provides decisions for general building planning and construction, and stands as the most important one. Apart from the Architecture code, the codes for parking zones, urban planning and housing development promotion are the sections related to housing construction in detail. The Code for housing development promotion is especially for providing and managing houses and flats of housing development at a large construction scale.

Table 3-2. Outline of the study of density in building regulations

Standard	Main regulatory criteria	Sub-regulatory criteria	Article
Indoor space	Building size	Building coverage	Article 47 clause 78
		Floor area ratio	Article 48 clause 79
		Plot and road	Article 33
Outdoor space	Spacing for setback	Spacing to front road	Article 51 section 1, Clause 82 section 2
		Spacing to the north	Article 51 section 1,2
	Parking lot facilities	Parking lot	RHDP: clause 27
		Road	RHDP: clause 26
		Play area	RHDP: clause 46
	Community facilities	Shopping facility	RHDP: clause 50
		Kindergarten	RHDP: clause 52
		Sport facility	RHDP: clause 53
		Public space	RHDP: clause 54
		Elderly centre	RHDP: clause 55

* RHDP: Regulation for Housing Development Promotion

As a first step to feed data on building regulations into a simple housing layout model, sections for the restrictions on building height and space for setback in housing plots has been found in the Codes mentioned above. For instance, building height is restricted by the distances from each building line to front road, the north. and adjacent buildings, according to the Codes that are described in a later section of the study. Secondly, among community facilities required to be allocated in housing development plan, the Code for housing development promotion provides for the type and area of some community facilities such as Play area, Shopping facility, Kindergarten, Sports facility, Public space and Elderly center. The minimum and maximum areas of the facilities required for the certain number of houses in the housing development are differentiated according to the type of the community facilities.

The building regulations together with the codes in this study are collected and applied on the basis of latest version that has been revised in June 1999.

3-2-1. Standards on Building Size

Table 3-3. Classification of land use

Main classification	Sub-classification	Type of housing and purpose
Residential area	Residential area I	A low building for detached house
	Residential area II-1	Detached house in general
	Residential area II-2	A low and middle story block of flat for attached house
	Residential area II-3	A high rise apartment building
	Residential area III	A residential building combining commercial use
Commercial area	Commercial area I	A building with business and commercial use in urban and sub urban area
	Commercial area II	A building with commercial related use in general
	Commercial area III	A building with general service for supplying daily necessaries in community
	Commercial area IV	A building to promote the circulation and distribution of goods connecting regional business
Industrial area	Industrial area I	A building related to heavy industries likely to produce pollutants
	Industrial area II	A building built with concerns of reducing pollution levels in community
	Industrial area III	A building related to light industries, housing residential use
Green-belt area	Green belt area I	Preservation for green space in urban area with issues of protecting natural environment
	Green belt area II	Reservation of land use for increasing agricultural products
	Green belt area III	A limited range of building development permitted to preserve green space

* Only one area proposed should be designated for a building

The Building regulation for land use constraints of constructing the type of buildings in designated areas has been specified in the Code for Urban Planning (Table 3-3). Since building size and its height bear obvious relation to the designated area, an investigation into areas in which the type of detached house for single family can be built needs to be made. Land uses for building the detached house according to the areas are given in detail in Table 3-4. For example, both the detached houses and the flats are permitted to be built for residential area-II by main regulation. However, for commercial area-IV, housing types for residential use are not permitted by the main regulation as well as the city ordinance.

Table 3-4. Land uses permitted for housing types according to the areas

Type of land uses		Building code	Detached house	Block of flats
Residential area	Residential area-I	Main regulation	●	○
		City ordinance	○	◑
	Residential area-II	Main regulation	●	●
		City ordinance	○	○
	Residential area-III	Main regulation	●	●
		City ordinance	○	○
Commercial area	Commercial area-I	Main regulation	○	○
		City ordinance	●	●
	Commercial area-II	Main regulation	○	◑
		City ordinance	●	◑
	Commercial area-III	Main regulation	○	◑
		City ordinance	○	◑
	Commercial area-IV	Main regulation	○	○
		City ordinance	○	○
Industrial area	Industrial area-I	Main regulation	○	○
		City ordinance	○	○
	Commercial area-II	Main regulation	○	○
		Main regulation	●	○
	Commercial area-III	Main regulation	○	○
		City ordinance	●	◑
Green-belt area	Green-belt area-I	Main regulation	●	○
		City ordinance	○	○
	Green-belt area-II	Main regulation	●	○
		City ordinance	○	◑
	Green-belt area-III	Main regulation	◑	◑
		City ordinance	○	○

● Permitted ◑ Partly permitted ○ Not permitted

As laid down by the regulation, areas proposed for the building type of the detached house are defined Residential area I, II and III along with Green belt area I and II. Apart from the regulation, the Ordinance, a law of a city or town, describes that Commercial areas (I, II) and industrial areas (II, III) are categorised in the area where the types of detached house are allowed to build in case a city or regional committee approves.

In order to find out appropriate ranges of land and plot uses of the detached type of courtyard house for theoretical model, the need to define the ranges of building coverage and floor area ratio of the areas arises.

3-2-1-1. Building Coverage/ Floor Area Ratio

Regulations designated for the ranges of the building coverage and floor area ratio of the detached house according to those areas are shown in Table 3-5.

Table 3-5. Ranges of building coverage and floor area ratio in the areas for detached house

Classification	Area	Building coverage	Floor area ratio
Areas (approved by main regulation)	Residential area - I	50/100 or less	100% or less
	Residential area - II	60/100	400%
	Residential area - III	70/100	700%
	Green belt area - I	20/100	80%
	Green belt area - II	20/100	200%
Areas (approved by city or town ordinance)	Commercial area - I	90/100	1500%
	Commercial area - II	80/100	1300%
	Industrial area - II	70/100	350%
	Industrial area - III	70/100	400%
No specification (made for land use)		60/100	400%

* Figures are expressed by ground area of building / plot area for building coverage and total floor area * 100 / plot area for floor area ratio

While the final decision is made by a city or town committee to control the proper ranges on site planning characteristics, the figures above can be adjusted where site conditions allowed or where fireproof structures are adopted in buildings. This rule applies to the building coverage in residential area (III) and commercial area (II), and the floor area ratio in residential area (III), commercial area (I, II), Industrial area (II, III) respectively.

3-2-1-2. Plot and road

According to the regulation (Article 33), a plot boundary should be adjoined a public road at least 2m or more for a building with the total floor area of under 2000 m^2 , and at least 4 m or more, whose width should also be 6 m or more, for a building of over 2000 m^2 . However, exceptions to the rule can be made in cases where planning a building on a plot may create easy access to the building or provide sufficient open space around the plot, thus approving itself to a person in charge.

3-2-2. Outdoor Space Standards

3-2-2-1. Building height and Spacing controls: Setback

External spacing in accordance with building height to plot boundaries towards front road, the south and north direction, and adjacent buildings is required in order to avoid congestion of buildings and provide amenities of good housing. Building regulations for constraints regarding the building height and outdoor spacing are found in RHDP: Article 9 section 1,2, Article 51 section 1, Clause 82 section 2 and Article 51 section 1,2.

1. Building height and spacing towards front road

Two ways of designating building height and spacing between the boundaries are specified in terms of front road. Firstly, a committee or a person in charge of regional development can give a public notification for maximum building height, taking into account urban development covering, efficient land use and including infrastructure for a long-term policy. Not only can the mayor of a city take over the responsibility of controlling the building height by establishing the city ordinance but the headman of a region or county decides on the ranges of the building height according to a building use.

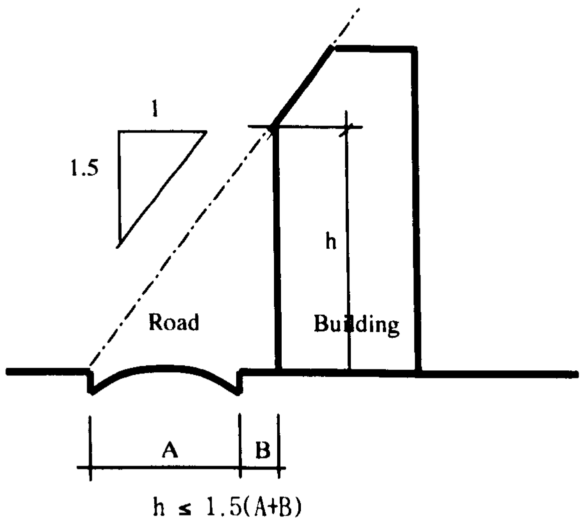


Figure 3-1. Relationship between building height and road width

In case of no indication being made in a building development for large scale, the maximum height of a building should not be exceeded more than 1.5 times to the total length of road width plus plot setback spacing on a horizontal distance. In addition, the local ordinance applies to the building height where a plot is adjoined by roads on more than two sides. Conversely if the distance is measured from the viewpoint of spacing on horizontal line, the requirement for the minimum distance of more than 0.67 times the building height from building edge to the opposite end of the road should be met (Figure 3-1).

2. Building height and spacing towards the south and the north directions

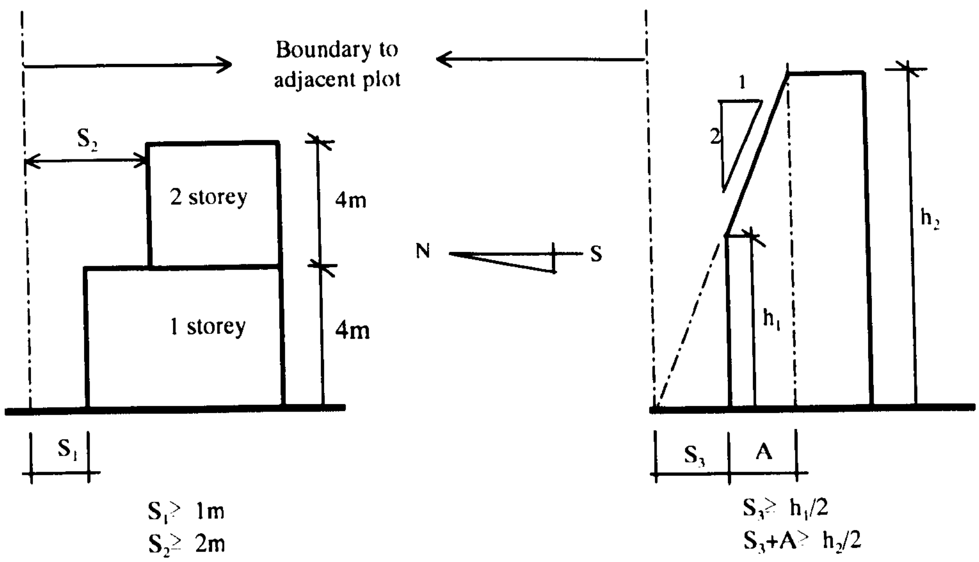


Figure 3-2. Relationship of building height to due north

Regulations for securing adequate daylight and sunlight are found in Article 51 section 1, 2 and Article 53 clause 86 as all types of building including houses and flats should follow the indications. There are also two types of the indication that applies, firstly, to a plot where spacing from the building edge to the plot boundary should be secured to the north and, secondly, to the plot with spacing to the south for adjacent buildings.

In residential area I or II, a building under 4 m high to the north direction should have the minimum distance of 1 m or over and a building under 8 m high should have 2 m or over from the building edge to the plot line without considering the number of building stories. Moreover a building with a height of more than 8 m should have a minimum distance of half its height for the spacing to the north (Table 3-6).

Table 3-6. Plot spacing to the north

Building height	Minimum spacing to the north
Height of less than 4 m	1m or over
Less than 8 m	2m or over
Over 8 m	Minimum spacing of 1/2 building height to north

A Second indication has been added to the regulations on the plot spacing since 1999 and, that is, the spacing needed for sunlight may apply to the south direction , in case where permitted by local ordinance, as well as to the north. The indication may be applicable to buildings constructed in a range of selected zones. These are;

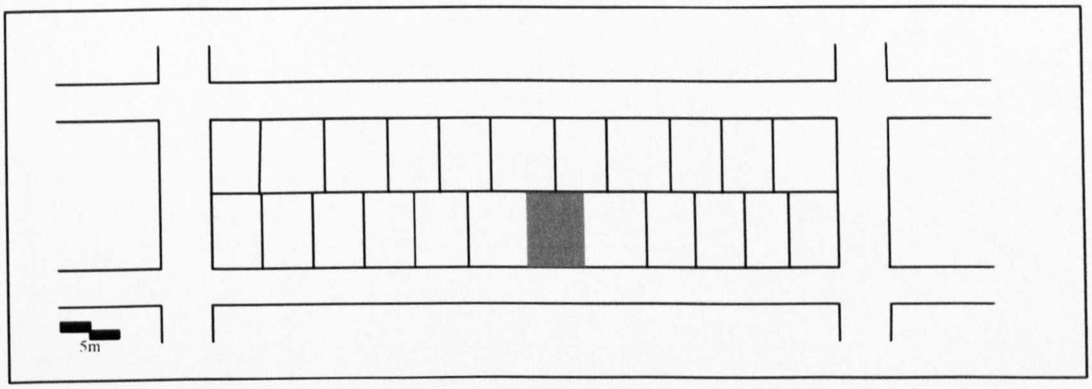
1. Zone of site development plan on large scale (Code for Site development Promotion: Article 3)
2. Zone of building plot development plan (Code for Housing Development Promotion: Article 33)
3. Zone for housing construction in operation (Code for Urban Planning: Article 2 ordinance 8)
4. Zone of multi-complex building in building development area on large scale (Code for the balance of regional development: Article 2 Ordinance 4,5 and 9)
5. Zone of national and regional development for industrial and agricultural complex (Code for industrial site and development: Article 6 and 8)
6. Zone of plot arrangement on process (Code for plot arrangement: Article 3)
7. Zone of housing re-development (Code for housing re-development: Article 4)
8. Zone of housing for improving environment (Code for improving environment for low-income class: Article 3)
9. A Plot adjoining to a road, public park and river to the north where no

construction of building is allowed

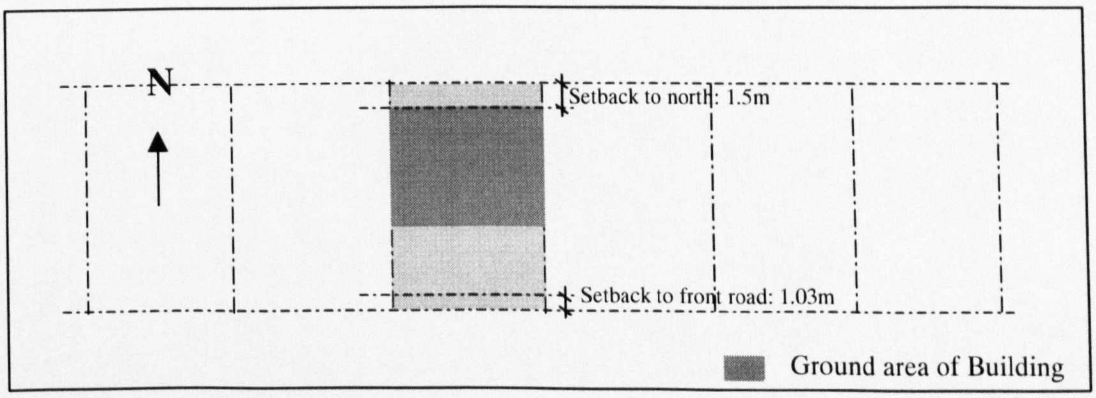
10. A plot whose owner obtaining mutual consent with the owner of adjoined plot

* Among the types of the detached house, the regulations for obtaining sunlight are not applied to the detached house for more than two families.

3. Case study; setback spacing



(a) Typical subdivision of urban development



(b) Siting of sample housing on plot

Figure 3-3. Typical examples of residential area of urban development

Source: P-H. Yoon (1988)

Figure 3-3 illustrates a typical example commonly found in the residential area-I in many urban areas. In this area, a house can be built with building coverage of up to 50 % under the building regulation codes. For example, under the assumption that a plot is utilised to its maximum for the marked plot (10m × 17.5m), the ground area of the house is about 87 m^2 for 175 m^2 of the plot size. If the height of the housing is set 9m (appox. 3 storey) and the depth of the front road is 5m, setback spacing is 1.03m to the front road and 2m to due north respectively. Accordingly, for the remained plot area of 88 m^2 excluding the housing ground area, the total area allocated for those setback spacing is 30.3 m^2, which marks nearly 35% of the total plot area. Although it is possible that setback spacing to the front road can be used for court area as shown in Figure 3-3 (b), setback spacing to the north still marks about 23% of the total area, without mentioning that the view and privacy of occupants toward east, west and north directions are nearly obstructed by adjacent buildings.

3-2-2-2. Car parking

Placing and sizing private or public parking space on the site are dealt in the codes for both housing development promotion and car parking lots. However the code for housing development promotion has priority over the code for car parking lot in case of where the both codes may be applied to a housing development.

To estimate the car-load for a large housing development site, according to the code for housing development promotion, a car parking unit is added to the total car parking spaces needed to the site in proportion to the net floor area of a housing unit (Table 3-7). It is also suggested, in general, that each housing unit should have at least one car parking unit or more. But an exception can be made in case where the net floor area of a housing unit is not more than 60m^2, 0.7 carload should be allocated to the site.

The code for car parking lots, on the other hand, provides another criteria that one car parking unit should be assigned for a detached house with the total floor areas of 130 m^2 or more and 200 m^2 or less. A car parking unit is further added to every floor area of 130 m^2 for a detached house with the total floor space of over 200 m^2.

Table 3-7. Criteria for Car parking space

Net floor area of house (m^2)	Criteria for car parking space (carload/ m^2)			
	Main city: Seoul	Main cities & some cities in metropolitan area	Small cities and counties in metropolitan area	Others
85 or below	1/75	1/85	1/95	1/110
85 or above	1/65	1/70	1/75	1/85

3-2-2-3. Community facilities

Of the articles prescribed by the regulation for housing development promotion, six types of community facilities that are described in relation to housing development density are chosen and specified below.

1. Play area

Play areas are required for a housing development as a minimum scale of 50 housing units or more. A minimum play area of 3 m^2 (2 m^2 for housing developments built in cities and counties) for each housing unit should be allotted for a housing development sized between 50 and 100 housing units. Again, a play area of 1 m^2 (0.7 m^2 in cities and counties) for each housing unit should be added to 300 m^2 play area (200 m^2 in cities and counties) for a housing development of over 100 units.

2. Shopping facility

The minimum area of the shopping facilities should not be exceeded 6 m^2 for each housing unit. But, in case the total area assessed on a basis of the calculation method is not more than 500 m^2, the total area for the facilities may be allocated up to 500 m^2 for the housing development.

3. Kindergarten

A site area used for Kindergarten for a community should be assigned for the housing development of more than 2000 housing units.

4. Sport facility

For a housing development of more than 500 housing units, a sport facility area of 150 m^2 for every 200 housing units should be added to the minimum sized area of 300 m^2. It is recommended that a court for the sport use such as tennis, badminton, volleyball, basketball or handball should be installed.

5. Public space

An area of 500 m^2 public space where facilities such as village office, police box and post office for public service should be ensured for a housing development with more than 3000 housing units.

6. Elderly centre

A housing development accommodating more than 100 housing units should have the minimum area of 15 m^2 for centre for the Elderly and an additional area of 0.1 m^2 in proportion to a housing unit in the housing development should be added to the basic area of 15 m^2. But a minimum area of 300 m^2 may be allowed in case of a total allocated area exceeding 300 m^2.

3-2-3. Summary of the Korean Building Practice Code on Theoretical Detached Housing Layout

By examining the building regulations related to housing density, it has been possible to find out some constraints on built forms which can be used as variables in a simple expression for the theoretical housing layout to investigate the relationships between housing density and solar access into the courtyard. The constraints are,

1. A minimum distance from the building edge to the opposite side of front road should be ensured more than 0.67 times the building height.

2. A distance from a building edge to a adjacent plot boundary to the north direction should have at least 1m for a building height under 4m, 2m for under 8m and 1/2 times its building height for over 8m.

3. An area of common facilities required for the community, which is varied according to the number of housing units in the local development. For the purpose of the study, criteria based on the six types of community facilities of a housing development unit, the facilities of which current building code provides the minimum and the maximum standard of outdoor community areas in order to enhance efficiency in land-use, are used. This is to measure the general proportion of plot-use allocation for the facilities to total plot area, which is to be embodied in density expressions. A community facility is selected only in case the building code clearly specifies the area of the facility. The relationship between the range of area for the facilities and the housing development unit is shown in Table 3-11.

3-3. The Model

3-3-1. Housing Layout Factor

In this section, the main purpose is to develop simple theoretical expressions of urban housing layout for courtyard houses with reference to density and its implication for usable plot and courtyard space. The developed models devised along with land use allocations provided by the building regulation are then compared and analysed using a computer program for passive solar housing.

To begin with, it is necessary to establish the relationships between usable net plot space and net courtyard space in proportion to the residential density. As shown in chapter 2, two typical examples of courtyard housing layouts in urban development have been identified for further density study on the basis that the types seem to best reflect the general principle of the urban site development plan. The types are,

1. Case A: a type of housing plot with a frontage toward E-W road, obtaining access from the north or south.
2. Case B: a type of housing plot with a frontage toward N-S road, obtaining access from the east or west.

By defining two examples, there are implications that the layout also affects the way of locating courtyard space and orientating individual rooms within a plot together with plot dimensions, according to the building regulations, relating to usable plot space. The housing layout factors which determine the solar energy availability may vary with many other variables, but the location, the dimension and the size of the plot under selected density standards in an residential area can be regarded as the prime factor relating to solar access.

Since many other variables such as latitude, slope, shape, surroundings, built purpose and orientation of a plot also affect the degree of solar access, a theoretical model is expressed in terms of minimizing influences generated by the variables. This study shows how the interrelationship among the individual factors such as plot size, dimension, location and building height can be defined on a series of usable courtyard space and its implications related to a range of solar accessibility to the spacing.

The expression for the theoretical model is made on the basis of the building regulations. However, in case where both a main building regulation and a local design practice, i.e. local ordinance, should be applied, it is assumed that a maximum or a minimum value of the regulation is then adapted to produce maximum courtyard spaces.

3-3-2. Theory; Courtyard Model

3-3-2-1. Measures of housing development density

Fist of all, it is necessary to deal with selected methods of measuring the density of development within residential areas of a neighborhood prior to defining and developing the density expression.

It is generally said that an appropriate level of densities should be secured in order to provide good open spaces for both solar accessibility and privacy on the level of an individual plot, and community facilities on a residential development site. Specifically speaking, the following standards should be established so that the amenities of good housing and its surroundings are ensured (e.g. County Council of Essex, 1973).

① Open space for sufficient sunlight and air flow on individual dwelling level
② Open space to secure a feeling of openness and privacy on a dwelling and

site development level

③ Open space usable to accommodate community facilities on site development level

The study on the intensity of residential use in terms of density expression has been dealt in various ways (Ó Catháin, 1977,78; Pollock 1982; De Chiara et al, 1984). Of the many methods of density measurement used for planning and regulatory purposes, three types of measurements – ① Net dwelling density, ② Gross dwelling density ③ Neighborhood density – have been commonly recognized and used in density calculations (DOE, 1973; De Chiara *et al*, 1984).

① Net dwelling density: The number of dwelling units per acre or hectare of net residential land (land devoted to residential buildings and accessory uses on the same lots, such as informal open space, drives, and service areas, but excluding land for streets, public parking, playgrounds, and non-residential buildings).

② Gross dwelling density: Gross density, a measurement much used in the past, is the number of dwelling units per acre or hectare of gross residential land (land as described above, plus bordering streets up to limited distances-ordinarily to the center of the street).

③ Neighborhood density: The number of dwelling units per acre or hectare of total neighborhood land (new residential land plus streets and land used for schools, recreation, shopping, and other neighborhood community purposes). Neighborhood land excludes non-neighborhood uses and unusable land within the neighborhood boundaries.

Any real layout will contain other land uses for community purposes such as spaces for school, shopping and so forth. To make the density expression as practical as possible, the measurement of neighborhood density relating to residential land use is employed in this study for the effect of density and solar access on courtyard housing.

3-3-2-2. A basic expression for development density

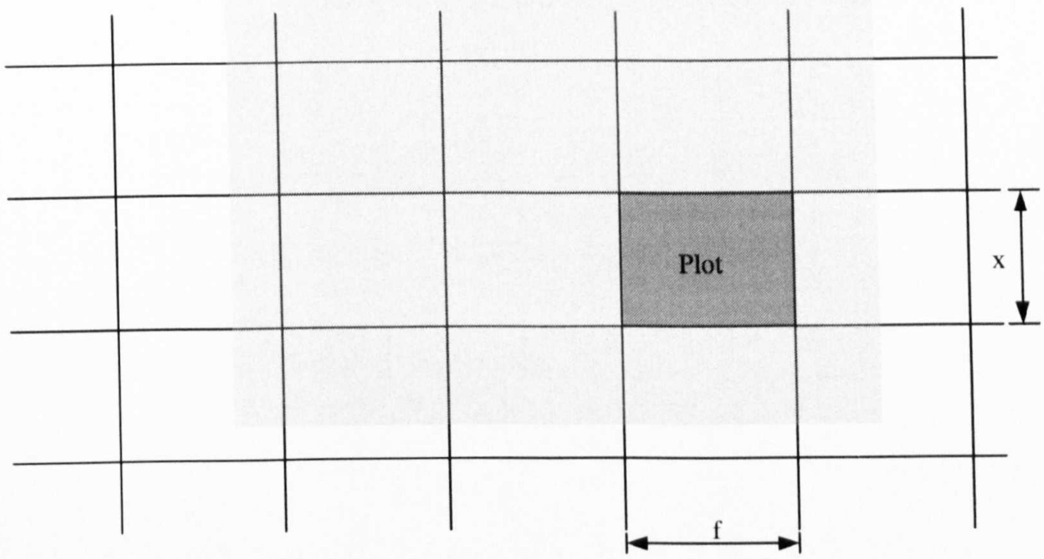


Figure 3-4. Basic housing layout on net dwelling density

In order to derive a simple expression for the concept of neighborhood dwelling density, initially, a housing layout with the net dwelling density concept, resulting in a larger plot size than the neighborhood density, is introduced at the preliminary stage for the expression. The basic housing layout shown on Figure 3-4 is a typical example. It shows a portion of a housing layout without considering other facilities for community uses such as land for street, public parking, playground and non-residential building as defined above. Basic housing density regarding to the number of housings per hectare is defined by x and f respectively. In this case, it is assumed that the given size of individual plots has the potential of containing other land uses for public roads and community facilities allocated for a unit area of residential developments.

Now, for a simple expression for the net housing density defined as the number of housings per unit area, it can be easily shown in equation (1) below that for a rectangular plot,

$$D = \frac{10000}{fx}(houses/hectare) \tag{1}$$

where D stands for density

f stands for plot frontage (m)

x stands for plot depth (m)

The arbitrary variable of x is to be defined in following section for the concept of the neighborhood density in more detail.

3-3-2-3. Standard representation of neighborhood density

The concept of neighborhood density has been introduced in order to meet density standards and avoid overloading community or citywide facilities. As a consequence, the importance of how to introduce the concept of open spaces for facilities in a unit area of urban housing developments has been emphasised.

It is determined for this study, that is to say, that its values on the usable plot size are to be varied in proportion to the amount of open spaces available for the community uses, provided that the open spaces are allocated equally to individual plots within a limited range of the development scale on site. The portion of open spaces allocated for community facilities is then converted into certain amounts of other land uses for individual plots so that the expression reflects the proportions of the actual land uses. As any real layout contains other land uses as explained above, these considerations for the other land uses will eventually result in a smaller plot size in actual use for housing building than a plot size derived from net dwelling density.

The land uses occupied by the facilities and the other uses by setback control designated for the building regulation within the individual plots are represented in Figure 3-5 as a series of notional strips at the back and boundaries of the plots respectively. Two types of the housing layout are presented to show how the setback controls on the housing layout can be affected by the relationship between plot location and front road. Here, the setback control for spacings to front road and due north are only considered. The setback controls on the variations of the plot are to be more specifically dealt in a later section.

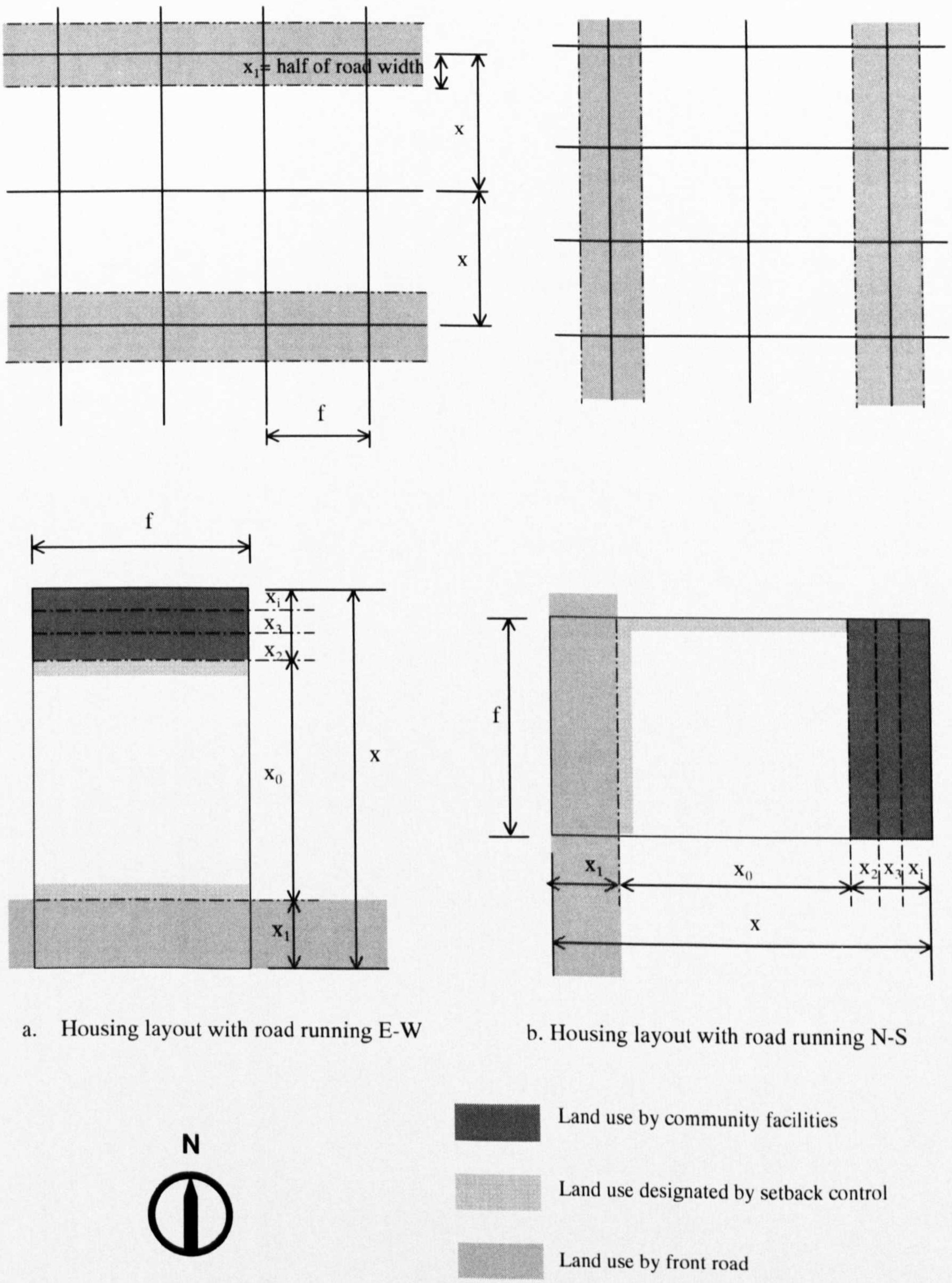


Figure 3-5. Housing layout facing roads with two direction and its land use per plot

In Figure 3-5, if the variables are labeled x_0, x_1, x_2, x_3 ... x_i and the value of f becomes constant, the amount of the net usable plot area, say fx_0, for building use becomes smaller as the proportion of the amount of the site for other land uses increases. It should also be recognised that the variables of x consisting of x_1, x_2, etc for plot depth represents to contain the area taken up by half of the road width and other land use allocation. This relationship is shown in equation 2a. Thus this makes it possible to express the relationship between net dwelling and neighborhood dwelling density. The relationships are graphically represented in Figure 3-7.

A. Plot depth: $x = x_0 + x_1 + x_2 + x_3 + \cdots\cdots + x_i$ (2a)

To set a simple expression for each land use allocation without reference to geometry, the values, a_i, for the sum of land uses per house allocated by official land use policy, i.e. building regulation, or land use practice determined empirically are introduced. If the value of a is put to expression (1), then it produces,

B. Land use for public road: $fx_1 = a_1$ (2b)

C. Land use for other community facilities: $f(x_2 + x_3 + \cdots + x_i) = a_2 + a_3 + \ldots + a_i$ (2c)

where a_i stands for the sum of minimum or maximum land uses per house allocated by land use policy: i.e. building regulation

The equations 2b and 2c provide the link between the allocated land uses for individual plot by the policy and the variables of f and x, thus implying a way to apply the data into the density expression that is to be developed. The advantage of the housing model is the production of an algebraic expression which links the housing layout factors and net ground courtyard area directly by expressing the area of net house plots as a proportion of the total area for the house site. It is also more realistic in terms of geometry.

Consequently, it becomes possible to proceed from any normal recommendation such as contemporary design and construction practice including regulatory purposes to a consideration of their effects on usable courtyard.

3-3-2-4. Relationship between plot space and courtyard space distribution

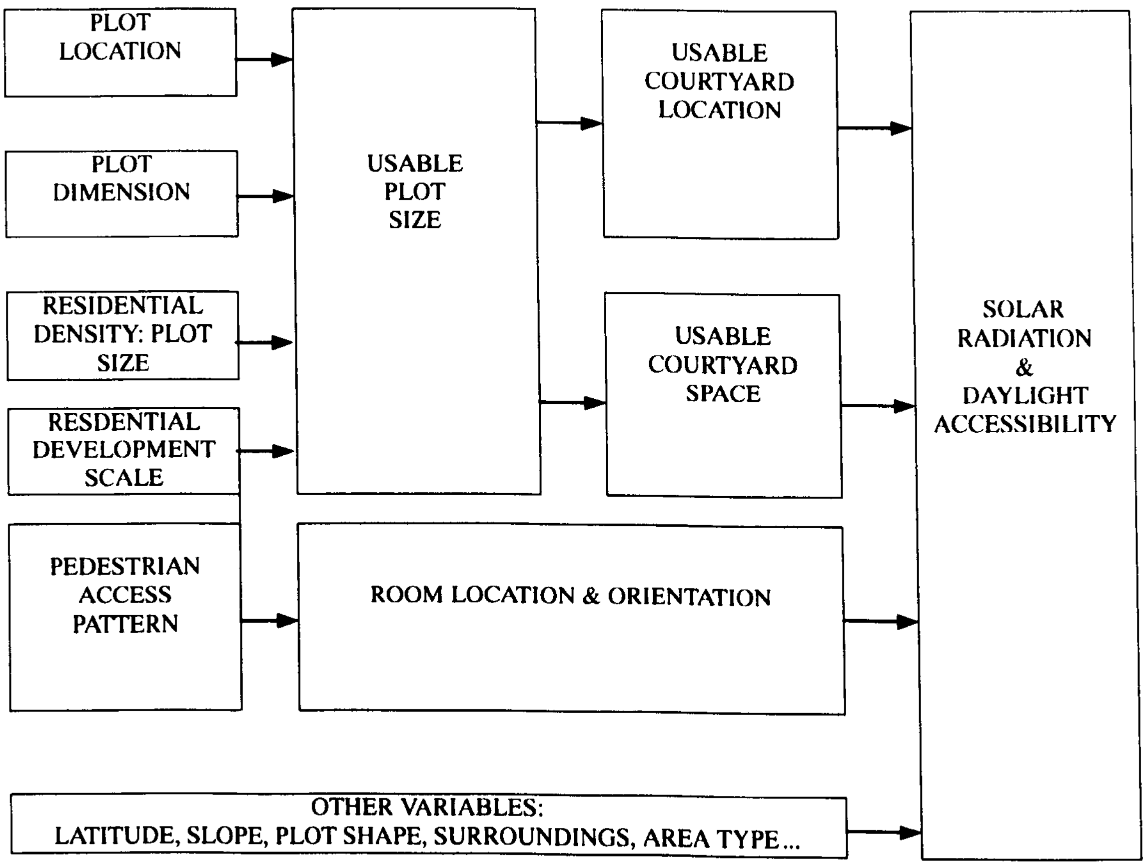


Figure 3-6. Diagram relating housing factors and solar radiation

As mentioned in section 3-3-1, there is a range of the independent variables, i.e. housing layout factors, which affect the size of usable plot and courtyard area and their corresponding solar radiation inside the area. Since the area of the useable courtyard is mainly a function of housing density, plot dimension, housing development scale and plot location, which then become a series of constraints for land-utilisation, emphasis is laid on how each of these functions constrains the area. The relationship between the variables and solar radiation / daylight accessibility is schematically shown in Figure 3-6.

1. Usable plot space

(1) Housing development density

As the housing density for a unit of residential development relates directly to the size of individual plots, the percentage of land covered by community facilities in the development also reflects the amount of space available for individual plots consisting of housing, courtyard and setback space and the like.

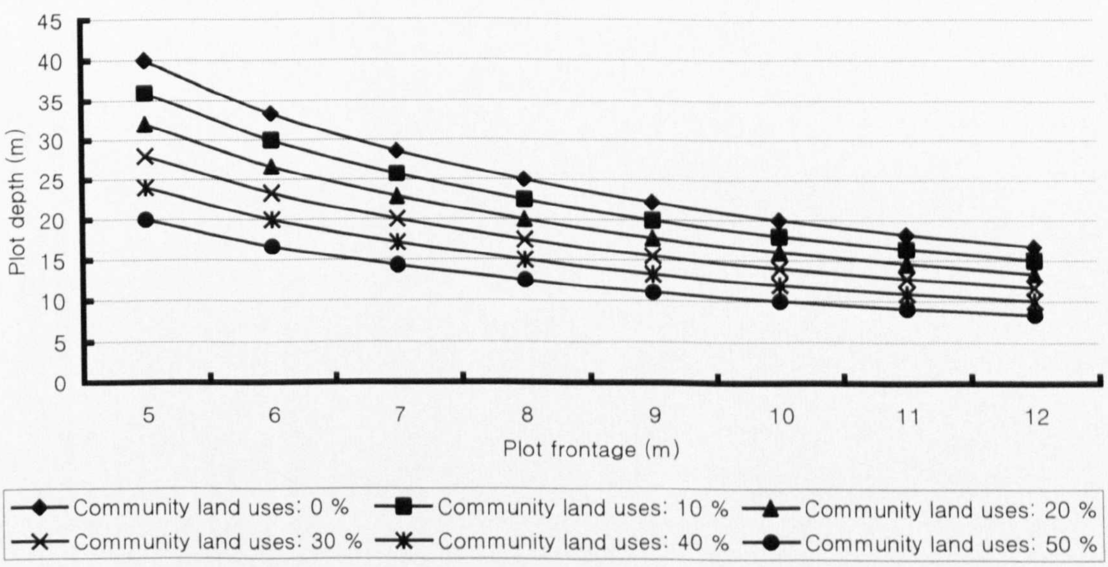


Figure 3-7. Plot depth variations for different community land use allocations of residential development in relation to average frontage variations
(Housing density: 50 units/hectare)

Figure 3-7, for example, shows a graph of the differences of plot depth corresponding to a range of plot frontage in terms of changing the percentage of allocated community land uses to residential development. In this example, the percentage of the community land uses ranges from 10 to 50 % (about one-tenth to half of the development land taken up by community uses) to examine the general tendency of the variations of the plot size based on the neighborhood dwelling density of 50 units/hectare.

By varying the percentages, it can be clearly seen that the ranges of the proportion of the usable plot size decreases as the amount of the land use allocation for the development increases. It also should be remembered that the larger the number of houses in a unit of the development, the less the amount of community land uses allocated for an individual plot. In either of those cases, the effects of increasing the percentage of community facilities or housing density become less significant with widening the plot frontage.

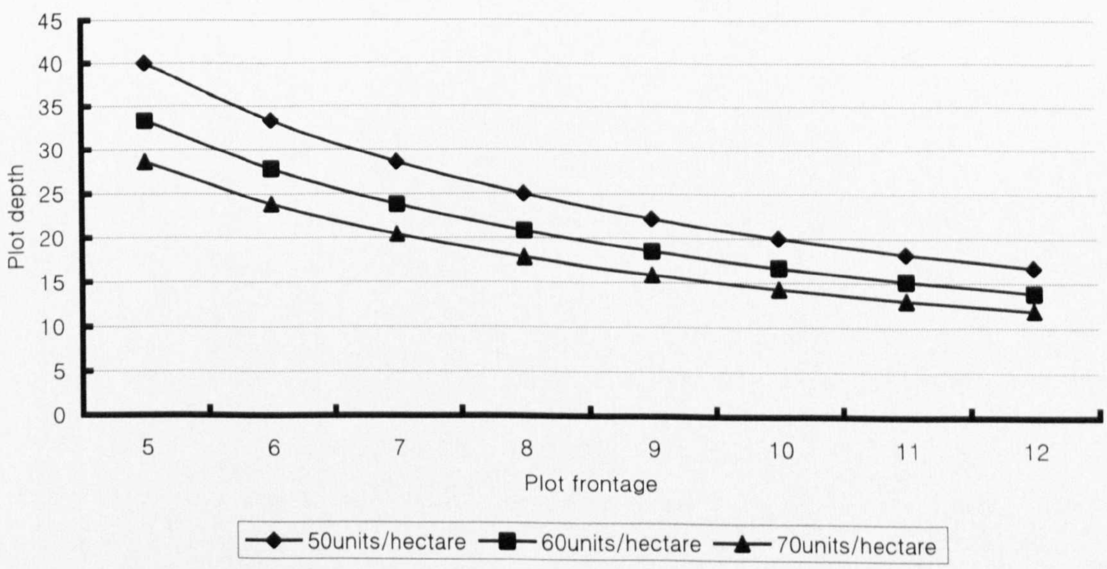


Figure 3-8. Plot depth variations for different housing densities of residential development in relation to average frontage variations
(Community land-use allocation: 0%)

(2) Plot location, dimension and building height

Referring back to the previous section, it is acknowledged that the ranges of total amount of usable net plot space, fx_0, are varied with a ranges of housing densities under the various mode of the intensity of residential use. Apart from the consideration of the community land uses and its implication to individual plot, according to the building regulation, the building height is one of the most important housing layout factors. Together with plot location and dimension, it impinges on the amount of setback spacing within the usable plot space.

To investigate the relationship between building height and setback spacing, two housing layout factors of ① Plot location and ② Plot dimension are used and thereby the interrelationships between the housing layout factor can be revealed.

Building height: Building height has an effect on setback spacing in relation to the spacing between building boundary and front road, and north as described in section 3-2-3 on the building regulations. Generally, the main building regulations take priority over the local ordinances in applying rules to buildings unless there are specific indications made by local committee. To estimate the effect on the spacings within usable plot space, the following are specifically important in relation to the building height.

① Building height and spacing towards front road: A minimum distance from the building edge to the opposite side of front road should be ensured to be more than 0.67 times the building height.

② Building height and spacing towards the north direction: A distance from a building edge to a plot boundary to the north direction should have at least 1m for a building height under 4m, 2m for under 8m and 1/2 times its building height for over 8m.

Thus it is possible to define the ranges of the effects of the plot dimension and location on the usable plot space in case of the building height being fixed.

Plot location and usable plot space: The plot location and orientation to the road are the main factors that determine the usable plot space. Since it can be seen that the street layouts both running N-S and E-W are the common system in the study on urban courtyard housing, the possible variations of plot location types being classified by the orientation of the plot to the road is shown in Figure 3-9. It shows how the location and orientation of the plot can be changed by the way the road lies, thereby shifting the main access to it. Accordingly the variation of the minimum distance as a setback spacing within a plot will occur in proportion of building height.

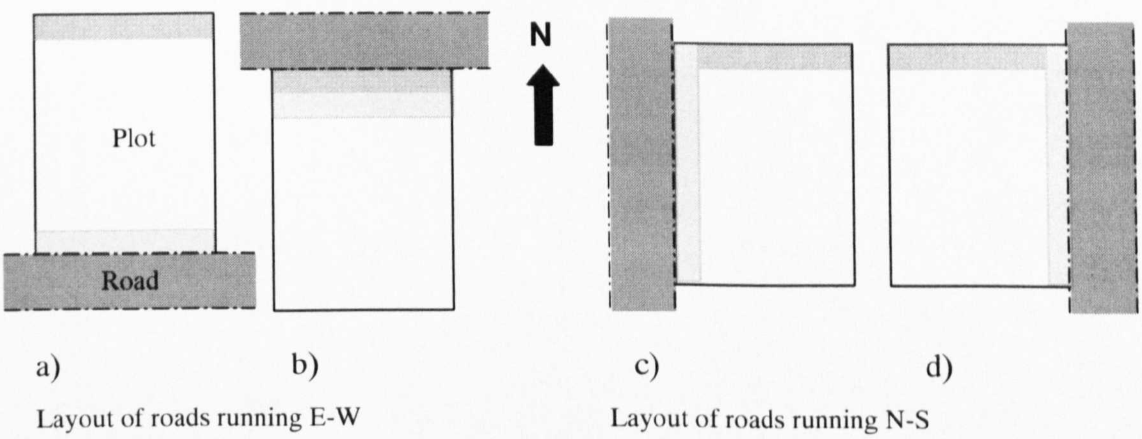


Figure 3-9. Four types of plot location and their ranges of setback spacing

Table 3-8. Plot location and setback spacing (spacing; m, area; m^2)

Plot location type	a		b		c & d	
	Spacing (m)	area (m^2)	spacing (m)	area (m^2)	spacing (m)	area (m^2)
Setback: front road	0.33	1.92	0	0	0.33	5.72
Setback: north	2	11.54	2	11.54	2	10.88
Total setback area	13.46		11.54		16.6	
Usable plot area	86.54		88.46		83.4	

* Plot dimension 1:3, size 100 m^2 , Road depth 5 m, Building height 8 m (approx. 2 storey)
* In case there are overlapped spaces in applying regulations, one with wider areas selected

In Table 3-8, for instance, the variations of the setback spacing and its corresponding area are specified as a shift of the location of the plot to reflect the setback spaces of different sizes. For a, b, c and d type plots, it is possible to say that the locations of the plot bear an obvious relation to the total area of setback spacing. By referring the way of application of setback spacing to the individual locations, on average, plot types such as c and d having N-S road in the development provide slightly better allowance for space available for siting housings than types a and b.

An example for the relationship between plot location and usable plot area is shown in Figure 3-10.

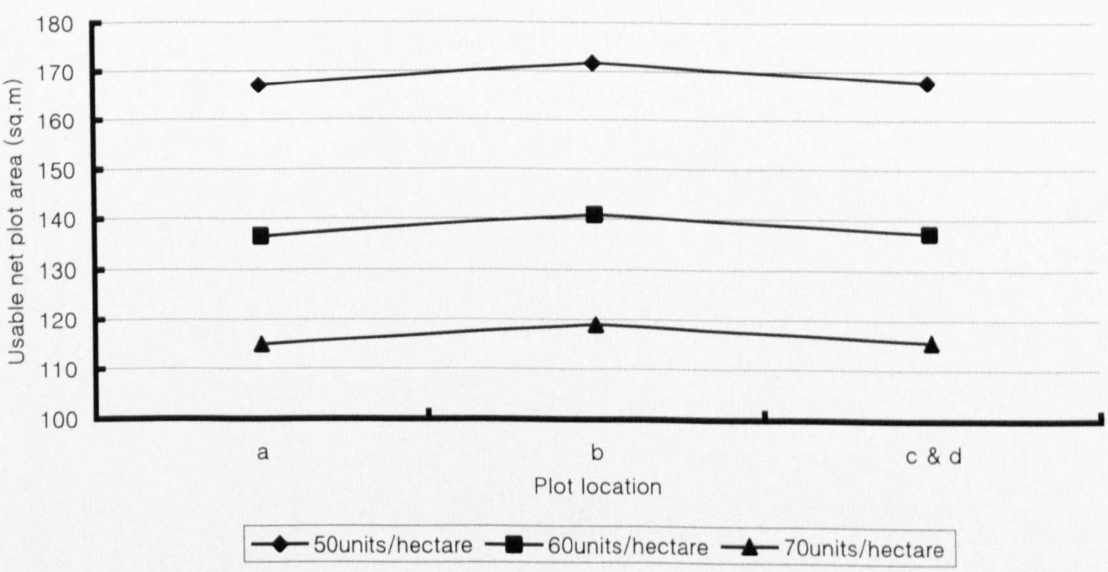


Figure 3-10. Variations of usable net plot area for housing densities based on four types of plot location

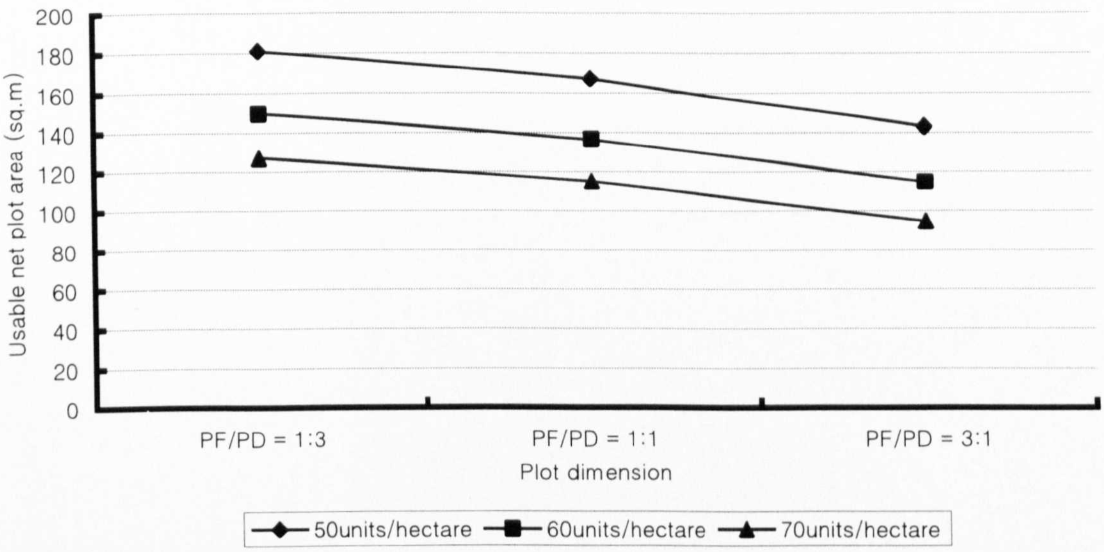


Figure 3-11. Variations of usable net plot area for housing densities based on the variations of plot dimension

Plot dimension and usable plot space: As many other factors are of importance, plot dimension also plays an important role in securing net usable plot area within an allocated plot without affecting the number of housings in a development unit. Table 3-9 gives an example of the variations of setback spacing and its corresponding total net plot area for a plot facing parallel road E-W with its access to the south.

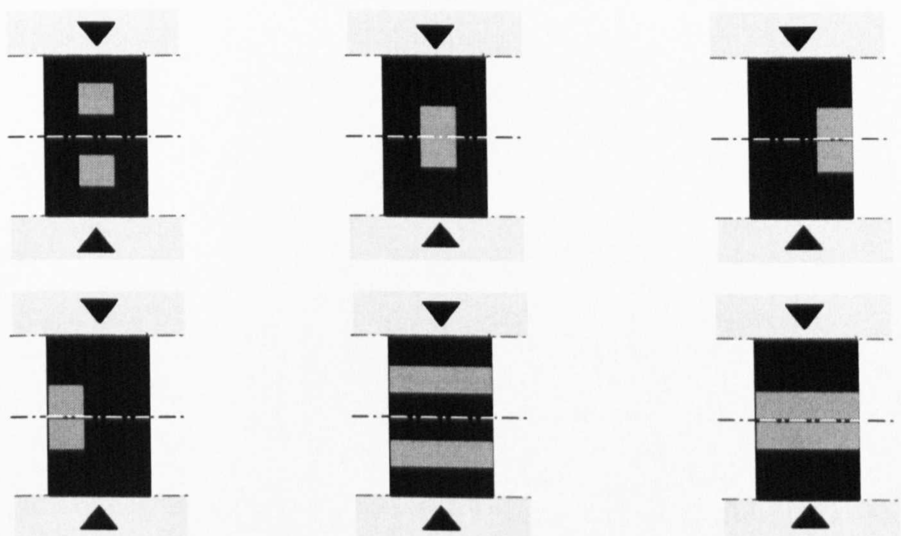
Table 3-9. Plot dimension and usable plot space

Plot dimension	f:x=1:5		f:x=1:3		f:x=1:1		f:x=3:1		f:x=5:1	
	Spacing (m)	Area (m^2)	Spacing (m)	Area (m^2)	Spacing (m)	Area (m^2)	Spacing (m)	Area (m^2)	Spacing (m)	Area (m^2)
Setback: front road	0.33	2.09	0.33	2.69	0.33	4.67	0.33	8.08	0.33	10.43
Setback: north	2	12.64	2	16.32	2	28.28	2	48.98	2	63.24
Total setback area	14.73		19.01		32.95		57.06		73.67	
Usable plot area	185.27		180.99		167.05		142.94		126.33	

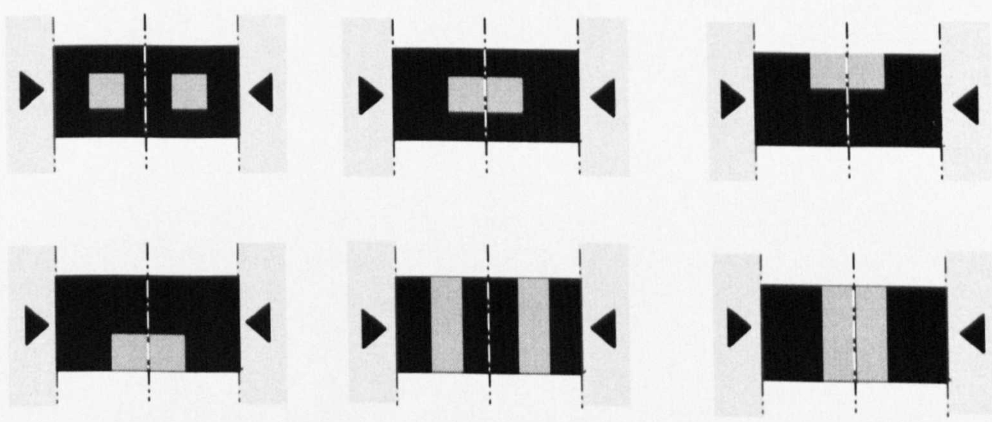
*Housing density; 50 units/hectare, Road depth 5 m, Building height 8 m (approx. 2 storey)

The possible combinations of plot dimensions of 1:5, 1:3, 1:1, 3:1 and 5:1 have been chosen for the housing density of 50 units/hectare which produces about 200 m^2 for individual plot size allocated. It is recognised by seeing the table that a plot with narrower frontage is prone to have more usable plot space.

2. Variation of courtyard plan on plot in relation to roads and access



Type A: Courtyard houses facing street running E-W with access to north and south



Type B: Courtyard houses facing street running N-S with access to east and west

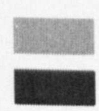


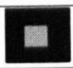
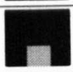
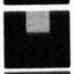
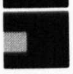
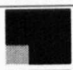
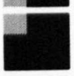
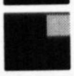
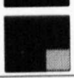
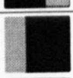
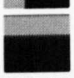
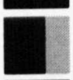
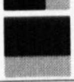
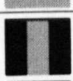
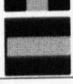
Figure 3-12. A ranges of standard generic courtyard types for two types of street layouts

Access to houses can affect the location of courtyard space, depending on plot and street layouts. Where access roads run in an east-west direction (Type A), houses can then be approached from the north or south. However, houses can be approached from east or west with access road running a north-south direction (Type B). In a convenient arrangement of the courtyard house plan, an introverted layout for courtyards is made to avoid direct contact with outsides of plot. With siting main buildings close to access roads, this allows for a series of the standard generic courtyard types according to the access. Figure 3-12 shows the alternative variations of the courtyard type houses for two road layouts based on the direction of access on a simple grid pattern.

Furthermore, the selections of the courtyard types are determined by not only plot location but also size and dimension to the allocated building ground area. Yannas (1994) points out that, for a given plot size, widening the plot will lead to a shorter depth and tighter spacing, and may cause overshadowing, emphasizing that spacing should be the first consideration. Plot frontage can then be considered in relation to the orientation of individual rooms. This implies that the housing layout factors need to be chosen in terms of courtyard geometry and solar energy availability.

Table 3-10 summarises the relationship between a range of courtyard houses and street layout patterns according to their road direction and housing access. This is to be used for identifying alternatives of possible courtyard models for a wide variation of usable courtyard space available in a density development.

Table 3-10. Relationships of courtyard planning to street layouts

Standard generic courtyard types:		Ranking of courtyard types according to road and access orientation			
		E-W street layout		N-S street layout	
	Standard grids of courtyard planning	Access to South	Access to North	Access to West	Access to East
	Centralized	●●	●●	●●	●●
	Semi-enclosed (U – shaped)	●	●●	●●	●●
		●●	●●	●●	●
		●●	●	●●	●●
		●●	●●	●	●●
	Semi-enclosed (L –shaped)	●	●●	●	●●
		●●	●	●	●●
		●●	●	●●	●
		●	●●	●●	●
	Attached	●	●	●	●●
		●●	●	●	●
		●	●	●●	●
		●	●●	●	●
	Linear	●	●	●●	●●
		●●	●●	●	●

(● Less suitable, ●● Suitable)

3-3-3. Application to Parametric Analyses

3-3-3-1. Introduction of 't' value

Prior to the development of a series of density expressions, a need arises to convert land use data into proportions of net land area. Thus the variable of t is introduced to measure the proportions of net land area to gross land area by considering areas taken up by other land uses for community facilities. For example, 0.9 of t value means that 10 % of gross plot area of a residential development area is assigned for other land uses for communities. The t value can be altered according to residential development size and density.

As previously stated in section 3-2-3, the land use allocations of community facilities for a series of residential development sizes prescribed by the building regulations are summarised in Table 3-11. Owing to priority being given to these six types of the representative facilities from the viewpoint of the urban residential development in the building regulation, the facilities are selected and used as a part of developing density expressions. It also makes sense in terms of maximising urban land-utilisation when adapting minimum and maximum regulatory limitations on land-use allocations.

By using those data, it gives information on land use allocation per house, the 'a_i' of standard representation (2), referred to in section 3-4-1 on the neighborhood density. This is then to be used to produce a series of t values corresponding to the variations of the sizes and densities.

Those facilities such as play area, shopping facilities, kindergarten, sports facilities, public space and the elderly centre of Table 3-11 are relabeled as a_2, a_3, a_4, a_5 and a_6 respectively in the order of application. This excludes an area, a_1, taken up for public roads, which will be dealt in a later section.

Table 3-11. Criteria for minimum and maximum land use allocation of community facilities of a series of housing development scales

(Land use allocation on the regulatory basis, m^2 per component uses)

The size of development / Community Facility	50 houses	100 houses	500 houses	1000 houses	1500 houses	2000 houses	3000 houses
Play area (min)	150	300	700	1200	1700	2200	3200
Shopping facilities (max)	300	600	3000	6000	9000	12000	18000
Kindergarten (min)	Recommended						
Sports facilities (min)	N.A	N.A	300	600	1050	1350	2100
Public space (min)	N.A	N.A	N.A	N.A	N.A	N.A	500
Centre for the elderly (min)	N.A	15	55	105	155	205	305

* N.A = not applicable

An expression for the relationship between the land use allocations contained in Table 3-11 and the land use allocation per plot with reference to the number of housings in the developments can be given as following (3).

$$\sum_{i=2}^{7} a_i = \frac{\sum_{i=2}^{7} A_i}{N} \qquad (3)$$

where a stands for community land use allocations per individual plot (m^2)

A stands for community land use allocations per the number of housings in a unit of residential development based on building regulation (m^2)

N stands for the number of housings in a development (unit)

Now, with the standard expression (3), the information contained in Table 3-11 can be converted into a table of the values for a series of unit housing developments (Table 3-12). The sum of a values, $\sum a_i$, are also shown for the range of the number of housings in residential developments.

Table 3-12. Land use allocations per each plot for the range of housing developments (m^2)

Housing Numbers / Land allocation per individual plot	50 units	100 units	500 units	1000 units	1500 units	2000 units	3000 units
a_2 : Play area	3	3	1.4	1.2	1.13	1.1	1.07
a_3 : Shopping facilities	6	6	6	6	6	6	6
a_4 : Kindergarten	0	0	0	0	0	0	0
a_5 : Sports facilities	0	0	0.6	0.6	0.7	0.675	0.7
a_6 : Public space	0	0	0	0	0	0	0.17
a_7 : Elderly Centre	0	0	0.11	0.105	0.103	0.103	0.102
Σa_i (m^2)	9	9	7.51	7.305	7.933	7.878	8.042

Table 3-12 indicates the sums of community land use allocations per plot according to the housing development variation, courtyards and roads at each scale of the number of housings for the development ranges from 7.305 to 9 m^2 . In other words, by changing the number of housing units for a development, the total area (Σ a), which is taken up by other community land-uses, allocated to an individual plot varies, thus producing various amounts of net plot area for building use.

$$t = \frac{fx - \sum_{i=2}^{7} a_i}{fx} \qquad (4)$$

where t stands for the proportions of net plot area to gross plot area in terms of considering areas for other land uses for the community facilities

As defined earlier, t value is devised to measure the proportion of net plot area to total plot area including allocations for areas taken up by community facilities but excluding public road area. To calculate t value for individual plot, it can be determined by the proportion of total plot allocation, fx, to the plot minus the sum of the a value as shown in the standard expression (4).

From the standard expression (1), the housing density is defined as the number of houses per unit area. By combining (1) and (4), and substituting 10000/D for the fx, total plot allocation, in the expression (4), then the following expression (5) results. Thus it is possible to identify the ranges of t values with using the 'a' value defined in Table 3-12 for the ranges of housing density (D).

$$t = \frac{10000 - D\sum_{i=2}^{7} a_i}{10000} \qquad (5)$$

Table 3-13. t value of density ranges for a series of residential development sizes

D (housing/ hectare)	N=50 (Σ a=9)	N=100 (Σ a=9)	N=500 (Σ a=7.51)	N=1000 (Σ a=7.305)	N=1500 (Σ a=7.933)	N=2000 (Σ a=7.878)	N=3000 (Σ a=8.042)
30	0.973	0.973	0.977	0.978	0.976	0.976	0.976
35	0.969	0.969	0.974	0.974	0.972	0.972	0.972
40	0.964	0.964	0.970	0.970	0.968	0.968	0.972
45	0.960	0.960	0.966	0.967	0.964	0.965	0.964
50	0.955	0.955	0.962	0.963	0.960	0.960	0.960

*D = housing density (housing units/hectare)

N = number of housing units

Table 3-13 shows the ranges of the t value, which have been calculated using equation (5), corresponding to a series of housing densities based on the ranges of the development sizes. For example, assuming that D = 45 units/hectare and N = 50 units for a development, the value for t is 0.96. Namely, in this case, at least the total plot area of about 96 % can be allocated to net plot area for building use as long as the development land is fully utilised to its maximum where the building regulation permits.

3-3-3-2. Road depth (x_1)

To define the net plot area of fx_0 for housing, the road depth, r, together with the setback spacing towards the road, S_r, and north, S_n, need to be considered. Since the half of the road width is included in the total plot area, fx, in terms of net dwelling density factors, the area represented as fx_1 can be expressed as below.

$$fx_1 = f\frac{r}{2} \tag{6}$$

where r stands for front road depth

In addition, the variations of the setback spacing toward the front road in relation to the road depth and building height and the spacing toward the north in relation to building height, respectively, should be considered to define the areas allocated for the other land use in net plot area. By simplifying the constraints of the building height and the road depth to the setback spacing, the two types of the spacing, named here S_r and S_n, are defined in the standard expression (7a, 7b and 7c). The height of each floor is 2.7 m, assuming the ground floor is to be located 1 m above the ground level based on current practice. The corresponding values for the road representing typical depth of 4 – 8 m are tabulated in Table 3-14.

$$h = 2.7 \times ns + 1 \tag{7a}$$

$$S_r = 2h/3 - r \tag{7b}$$

S_n = 1 m: building height of 4 m or less (7c)

2 m: building height of 8 m or less

0.5h: building height of more than 8 m

where h stands for building height

ns stands for number of stories

S_r stands for setback spacing towards front road

S_n stands for setback space towards the north direction

r stands for front road depth

Table 3-14. Variations of setback spacing based on the ranges of building height

Road depth (r)	Setback spacing (m)	1 storey	2 storey	3 story
		3.7 m	6.4 m	9.1 m
4 m	S_r	-1.53	0.26	2.07
	S_n	1	2	4.55
4.5 m	S_r	-2.03	-0.23	1.57
	S_n	1	2	4.55
5 m	S_r	-2.53	-0.73	1.07
	S_n	1	2	4.55
5.5 m	S_r	-3.03	-1.23	0.56
	S_n	1	2	4.55
6 m	S_r	-3.53	-1.73	0.07
	S_n	1	2	4.55
6.5m	S_r	-4.03	-2.23	-0.43
	S_n	1	2	4.55
7 m	S_r	-4.53	-2.73	-0.93
	S_n	1	2	4.55
7.5 m	S_r	-5.03	-3.23	-1.43
	S_n	1	2	4.55
8 m	S_r	-5.53	-3.73	-1.93
	S_n	1	2	4.55

* Figures do not always yield positive values. This reflects that sometimes negative values appear where building height is low enough to have each plot served without considering setback spacing, thereby indicating the negative value can be replaced by '0'.

3-3-3-3. Density expression for usable courtyard space

The importance lies in the relative performance by reference to solar access of alternatives of courtyard spaces available in relation to changing the housing layout factors rather than actual predictions in this study. Thus assumed values have been chosen corresponding to the following criteria.

① The courtyard building is single unit having intensive use within a plot space.

② An equal distribution is made in terms of the size of plot according to the ranges of housing densities for the residential development.

③ The front road is assumed 5.5 m in depth including footpaths on both sides.

④ The building consists of same geometrical structure, thus its floor areas are equal for each floor.

⑤ The courtyard has minimum internal obstruction.

⑥ Car parking lots are assumed to be allocated equally in each house plot.

⑦ The roof of the courtyard house is assumed to be flat

⑧ Minimum value of zero for setback spacing to adjacent buildings is assumed.

⑨ The level of the surface between the grounds of building plot and front road is assumed to be same.

⑩ Parametric variations of the housing layout factors are made to assess solar availabilities (Table 3-15).

Table 3-15. Standards on parametric variations

Housing layout factors	Base value	Parametric variations
Housing density (units/hectare)	50	30 - 50
Plot dimension (m)	15	5 - 25
Housing development scale (units)	500	50 - 1500

* Common values are taken based on studies (NBA, 1970; J. D. Chiara et al, 1984)

The parametric variation of the housing layout factors would then generates a series of courtyards on their sizes and hence which location on plot the courtyard lies. The courtyard space available on the plot is considered as a function of the interactions of the housing layout factors.

In order to study simple housing layouts in a parametric fashion for urban developments, there needs to be a limit to the number of cases, and the theoretical models of housing plot with parallel streets running E-W and N-S are modelled in the order of orientation. Therefore, these housing models can be subclassified into plots facing street E-W with its access to the south and north, and plots facing street N-S with access to the east and the west in accordance with the ranges of setback spacing application. Since the setback spacing application to both N-S street cases with access to the east and west is found to be identical, the density expressions for three types of theoretical housing models according to their orientations are set out below.

The calculation of net plot area (A_p) can be defined in the expression (8a) as

$$A_p = fx - fx_1 - f(x_2 + \cdot \cdot \cdot + x_7) \tag{8a}$$

By substituting $f(x_2 + \cdot \cdot \cdot + x_7)$ for $\sum a_i$, i.e. land allocation per individual plot, the expression (8a) can be rearranged for housing layout in all three types of housing layout as shown below,

$$A_p = fx - \sum_{i=2}^{7} a_i - fx_1 \tag{8b}$$

Thus, the calculation of net courtyard area (A_c) can be defined in the expression (9a) as

$$A_c = fx - \sum a_i - fx_1 - f(S_r + S_n) - A_g \tag{9a}$$

where A_c stands for usable courtyard space

A_g stands for ground area of housing unit

for a housing plot with parallel streets running E-W with access to the south.

$$A_c = fx - \sum a_i - fx_1 - fS_r - A_g \quad (S_r \geq S_n) \tag{9b-1}$$

$$A_c = fx - \sum a_i - fx_1 - fS_n - A_g \quad (S_r \leq S_n) \tag{9b-2}$$

for housing layout with parallel streets running E-W with access to the north.

$$A_c = fx - \Sigma a_i - fx_1 - fS_r - S_n x_0 + S_n S_r - A_g \tag{9c}$$

for housing layout with parallel streets running N-S with access both to the east and the west.

If the density expressions of (1), (5), (6) and (7) are put to the expressions (9a), (9b-1), (9b-2) and (9c), respectively, net plot area (A_p) can be defined in the algebraic expressions as

$$A_p = \frac{10000}{D} \cdot t - f \cdot \frac{r}{2} \tag{10}$$

for housing layout in all three types of housing plot.

As to calculation of net courtyard area (A_c), it can be defined as

$$A_c = \frac{10000}{D} \cdot t - f \cdot (\frac{r}{2} + S_r + S_n) - A_g \tag{11a}$$

for housing layout with front road running E-W with access to the south

$$A_c = \frac{10000}{D} \cdot t - f \cdot (\frac{r}{2} + S_r) - A_g; (S_r \geq S_n) \tag{11b-1}$$

or

$$A_c = \frac{10000}{D} \cdot t - f \cdot (\frac{r}{2} + S_n) - A_g; (S_r \leq S_n) \tag{11b-2}$$

for housing layout with road running E-W with access to the north

$$A_c = \frac{10000}{D} \cdot t - f \cdot (\frac{r}{2} + S_r) - S_n \cdot (\frac{A_p}{f} - S_r) - A_g \tag{11c}$$

for housing layout with road running N-S.

Hence, Building coverage = A_g / A_p

Floor area ratio = $(A_g \times ns) / A_p$

Courtyard area ratio = A_c / A_p

Summary of the Chapter

The aim of this chapter is to derive a series of density expressions for the relationship between various housing layout factors and net courtyard areas with their corresponding solar gain. In order to do this, this chapter has looked at a selected number of constraints on a built form which are taken to be directly influential in forming the usable net courtyard area, leading to examining the current building regulation codes.

By investigating the Korean building regulation codes relating to a courtyard housing layout, the constraints are selected and defined. The relevant aspects of the building codes, which can be used as criteria are; Firstly, a minimum distance from a building edge to the opposite side of front road should be ensured according to building height. Secondly, minimum distance between the building edge and the boundary of an adjacent plot should have certain distances. Lastly, an area of common facilities required for community is varied according to the number of housing units in a local housing development. The selected number of the constraints, i.e. setback spacing to front road, setback spacing to due north and community facility allocations, has been used as criteria in developing the density expression for simple theoretical models of courtyard housing layout.

By converting the criteria into simple variables for the standard density representation of neighborhood density, a series of density expressions are developed in the last part of this chapter. For instance, six community facilities specified for minimum and maximum areas in the building codes are selected and abbreviated as 't' value in the expression in order to determine the relationship between requirements of the building codes and the house plot. The selected factors, such as housing density, plot dimension, housing development scale and plot orientation (E-W and N-S street layout), are directly related to net courtyard area and corresponding solar radiation. Then, the expressions are applied to the assessment of effects of varying certain housing layout factors in courtyard design. A range of net courtyard areas produced by varying the factors in the density expression is assessed for the amount of solar radiation on the principal courtyard facades using a computer tool, Shadowpack (Chapter 5). Interpretations of results and analyses for urban courtyard housing will be shown in terms of changing housing stories (Chapter 6). Thereby guidelines for suitable ranges of the design parameters of courtyard housing are to be suggested.

Chapter 4

The Computer Program; A Tool for Solar Radiation Assessment for Courtyard Housing Models

4-1. Introduction

Many programmes are now available to aid in building design, simulation and analysis from an environmental point of view. For the research described in this thesis, it was decided to select a relatively straightforward and easily available programme, Shadowpack – P.C. Version 2.0.

Since the operation of the programme is based on geometry and relatively well understood and accepted algorithms, it was not considered necessary to undertake a detailed evaluation before making the choice. As a prelude to use of the programme, the author had carried out a large number of tests using simple building shapes used with a mechanical heliodon. This served the author understanding of the underlying principles.

As stated, the computer program package, Shadowpack – P.C. Version 2.0, that has been developed for assessing the direct or the global (direct + diffuse) solar radiation on building facades is introduced for courtyard housing models for this study. The programs are written in Fortran and makes limited use of the GINO-F graphics package (Peckham, 1985, 1989, 1990).

The programs allow the user to assess the amounts of solar radiation of courtyard facades of any proportion, size and orientation at any location on a monthly basis by creating a 3D model of courtyard housing models. The package described here allows the user to first construct the 3D model, using the interactive, solid modelling program ICON. The model description can then be written to a data file for subsequent analysis and display by three other programs. The names and functions of the programs are summarized below:

① ICON, for interactive construction of the 3D model

② SHADEN, to calculate the direct energy received on particular faces, or all faces of the model

③ GLOBAL, to calculate the global (direct + diffuse) energy received on the faces of the model

④ ISOSUN, to compute and plot the distribution of direct radiation received over a particular face, or over the ground.

4-2. Description of the Programs; Shadowpack package – P.C. Version 2.0

A typical sequence in such an analysis is to first create the model using the interactive program ICON, and save it on a sequential data file. Then quantitative values for the energy received on particular faces of interest of the model can be tabulated with the programs SHADEN and GLOBAL, and, if necessary, contour plots of the distribution of radiation over individual faces can be created with ISOSUN. A descriptive outline of each program is presented below. In addition, further information on the model with some examples are illustrated in Appendix 3.

4-2-1. ICON

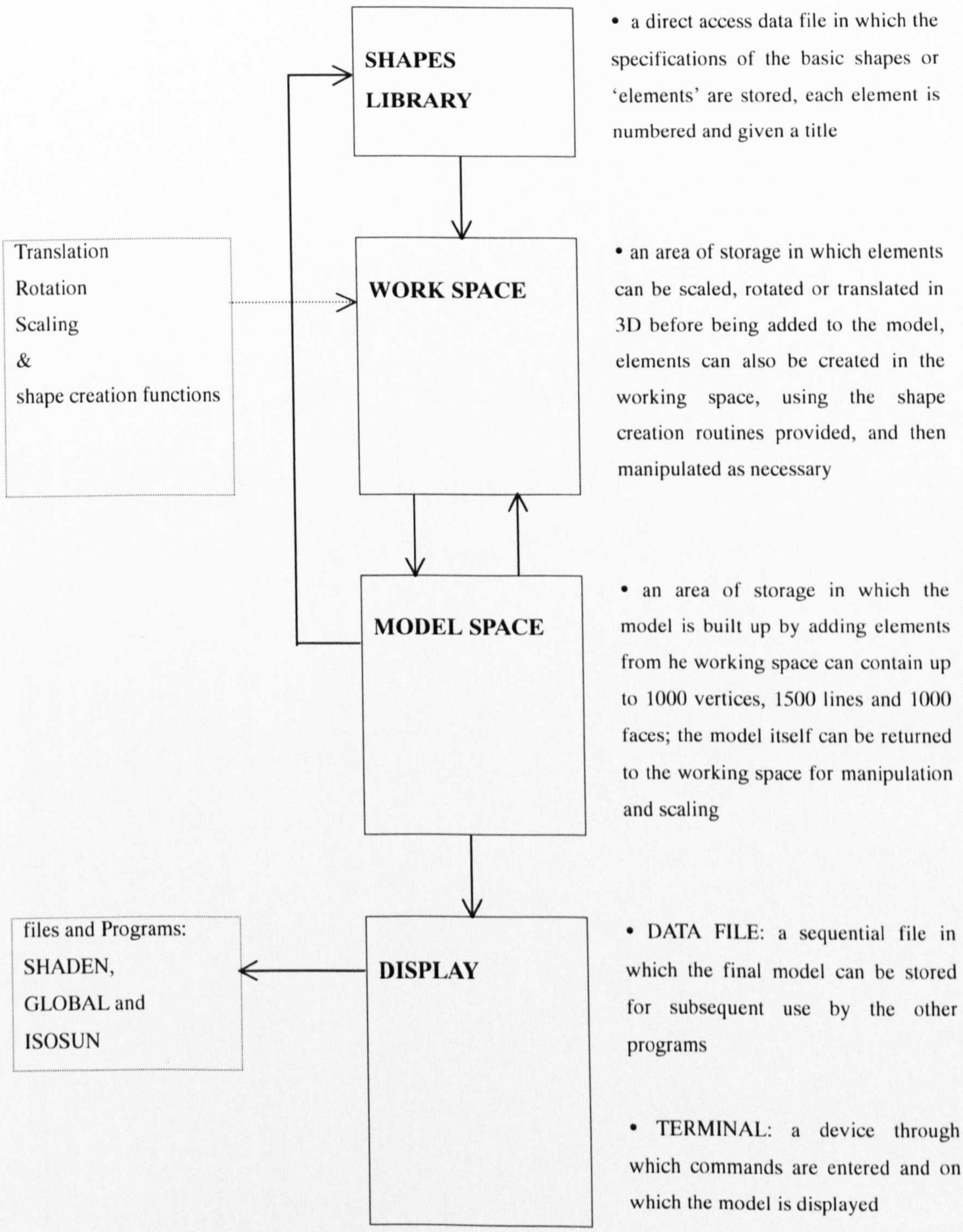


Figure 4-1. Operation of ICON

Source: Robert J. Peckham (1985, 1990).

ICON is an interactive program to facilitate the construction of the three dimensional model and its storing on file for subsequent analysis by the other three program, i.e. SHADEN, GLOBAL and ISOSUN.

A library of basic shapes can be accessed and these shapes can be manipulated in 3D before being added to the model. The shading pattern generated from the model is that corresponding to the direct solar radiation for a chosen latitude, time and day of the year. In addition to using the library of basic shapes, the program also has subroutines for the creation of certain geometrical forms by entering the appropriate parameters. These basic forms include polygonal faces, prisms of polygonal cross section, cylinders, spheres and surfaces of revolution. Facilities for other forms can be added as they become necessary. Once created, the model can be added to the library of shapes or written to a separate data file for use by the other four programs. The method of operating the program is shown schematically in Figure 4-1.

4-2-2. SHADEN

The program SHADEN calculates and tabulates the amount of direct solar energy incident on a number of model faces of interest. The calculation is performed either assuming clear skies all of the time, or using TRY data (Test Reference Year Data) for the direct component of solar radiation.

The results are recorded at intervals of fifteen minutes for four days per month for the chosen period of months. The days are spread evenly through the month. For each time the model is transformed into the sun's view frame and the faces of interest are scanned to find the area seen by the sun. The areas are multiplied by the incident direct radiation (taken from TRY data, or assuming clear skies) and the values integrated to find monthly totals for each face of interest. In order to save computing time, the calculations are not made for every day of the year but sampled at one week interval, i.e. four days per month. This is possible because the declination of the sun changes only slowly with time (3° /week at the most). The 4th, 11th, 18th and 25th day of each month are chosen, and the average of the energy received on these four days is scaled by the number of days in the month. The procedure for determining the energy received on the faces of interest is shown in Figure 4-2.

(1) calculate the azimuth and elevation of the sun

(2) calculate the intensity of direct solar radiation, MJ/sq.m

• This is done assuming clear sky conditions, or by interpolating hourly Test Reference Year (TRY) Data

(3) Transform the model to a coordinate system x, y, z

• The z axis points towards the sun; the coordinates x, y thus give the projection of the model as seen from the sun's direction

(4) Test the face of interest for self-shading. If shaded go to step (8), otherwise continue with next steps

• This is done by testing the sign of the z component of the face normal

(5) Scan the face of interest in the coordinate system x, y

• For a scan point to be shaded it must lie within and behind the projection of another face as seen from the sun

(6) Calculate f the fraction of area shaded

• The area shaded is equal to the number of shaded scan points divided by the total number of face

(7) Calculate the energy received per sq.m of the face, using equation; $900 (1-f) / \cos \theta$

• θ is the angle between the sun's direction and the normal to the face, and 900 is the number of seconds in the 15 min smapling interval

(9) Repeat steps (4) – (6) for each face of interest

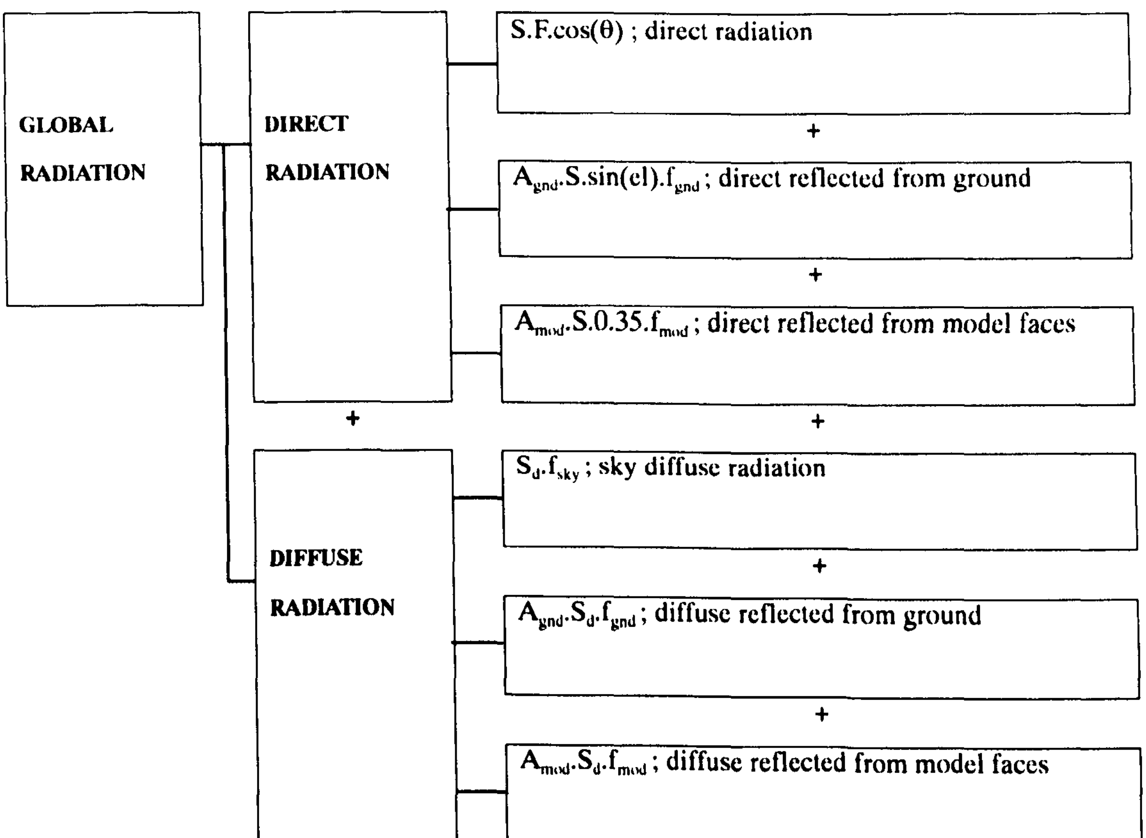
(10) Make monthly summations for each face of interest

Figure 4-2. Flow chart for the calculation procedure of SHADEN

Source: Robert J. Peckham (1985).

4-2-3. GLOBAL

The program GLOBAL calculates the amount of global (direct + diffuse) solar energy incident on a number of model faces of interest. The calculation is performed using TRY data for the direct and diffuse components of the solar radiation.



* θ is the angle between the sun's direction and the normal to the face of interest, F is the fraction of the faces area which is not shaded, and el is the sun's elevation

Figure 4-3. The components of the global radiation
Source: Robert. J. Peckham (1990).

In order to calculate the global radiation G, the model requires a value for the albedo of the ground, a_{gnd}, and a value for the albedo of the model faces other than the ground, a_{mod}. All model faces other than the ground plane are assumed to have the same albedo. For each of the faces of interest shape, factors are calculated for the sky f_{sky}, the ground f_{gnd}, and other model faces f_{mod}. These represent what fraction of solid angle the faces see that is composed of sky, ground and other model faces. Diffuse radiation is assumed to be uniformly distributed over the sky. Representing the direct solar radiation by S watts/m^2 , and the diffuse radiation on a horizontal surface by Sd watts/m^2 , the global radiation received on a face is approximated by six terms as shown in Figure 4-3. As with the program SHADEN, the procedure of the calculation method for determining the intervals of the chosen period, and for evaluating the results is made on a monthly basis.

4-2-4. ISOSUN

The program ISOSUN is designed to make a contour plot of the amount of direct solar energy incident on a particular model face of interest integrated over a chosen series of months. The program makes use of the same file of geometric data as described previously, and the face to be investigated must be specified in the control data of ICON program.

A grid of sampling points is created on the face under investigation and the radiation received is calculated at these points using the same method as described in the previous section. At each time the model is transformed into the sun's view frame and each grid point is tested for shading. If the grid point is not shaded the direct energy arriving is integrated in the appropriate array element. The two dimensional array of results is then used to make a contour plot. The intensity of direct solar radiation is computed either by assuming clear skies, or by interpolating hourly TRY data. The task of ISOSUN is split into two steps, i.e. computation phase and plotting phase. The computation phase is performed by ISOPREP and the plotting phrase by ISOPLOT. ISOPREP saves the results on a file which can be read by ISOPLOT.

4-3. Application of the Program to Courtyard Housing Models

4-3-1. General Remarks

The results of the amount of solar radiation are based on the computer program package, SHADOWPACK –P.C. Version 2.0. The programs respond to various parameters such as orientation and form in a simplified way. For the purpose of the study, of the programs, ICON and SHADEN are adapted and applied for Seoul located in latitude 37.34°N.

Using the algebraic expressions developed for urban land-use in chapter 3, a series of usable courtyard areas and its corresponding three- dimensional courtyard housing models are created and shadows cast by their shapes were then visualised with the program ICON. Then, the program, SHADEN, was used to calculate the direct solar radiation with weather data in the form of Test Reference data (TRY) which selects four days per month and then produces results for the whole of the selected month. Sky conditions are assumed to be clear at all times and the albedo values on the courtyard surface are not taken into account. The simulation was to be carried out assuming a flat site over the three main months of the cooling period from June to August, and the heating period from December to February respectively at latitude 37.34° N. For each case of courtyard geometry, the seasonal averages of the monthly direct solar energy of the surfaces of the four walls of the courtyard model are calculated. This would seem a valid system to employ since it is the opaque and particularly the transparent surfaces of the buildings which give rise to solar heat gain. However, the solar energy of ground surfaces is excluded as the emphasis of this study is placed on relative comparisons of the housing layout factors.

To illustrate the effect of the housing layout factors, three cases of building height are considered, 3.7, 6.4 and 9.1 metres, that correspond to models of one, two and three storey housing respectively.

4-3-2. Notes and Limitations of the Program

The scanning intervals, are specified in terms of the model dimensions. The calculation assumes the model dimensions are in metres, calculates areas of faces in square metres, and gives results in MJ/sq.m. Scanning intervals of about 1/10th of the face dimensions, giving of the order of 100 scan points across a face, should be sufficiently accurate for most purposes. Finer scanning intervals increase the accuracy but rapidly increase the computing time. In addition the limit on the number of faces to be analysed is 10.

Summary of the Chapter

The computer program package, Shadowpack- P.C. version 2.0, is a useful tool to calculating the amount of solar radiation quantitatively for the facades of buildings. Various modes of estimating solar radiation can also be accomplished by carefully choosing the computer programs, such as SHADEN, GLOBAL and ISOSUN after constructing 3D model by using interactive program ICON.

As the purpose of the study is to seek for relatively advantageous courtyard housing forms in urban housing layouts comparatively, the programs, ICON and SHADEN, which is effective tool to embody 'direct solar radiation' recorded in building facades of interest, are adapted and applied for Seoul, at the latitude of 37.34° N. The assessments for the effect of direct solar radiation on housing models are made over three months of the cooling period from June to August, and of heating period from December to February.

Chapter 5.

Results of Simulation for Urban Courtyard Housing Model

5-1. Introduction

5-1-1. General

The problem posed was to examine the implications of varying the housing layout factors and the consequent amounts of solar radiation for the ranges of courtyard space available in Seoul, Korea, under current building regulation. In general, to ensure adequate area for courtyard space inside housing building, one should take account of the housing layout factors such as plot size (housing density), plot dimension, plot location and housing development scale. However, a question arises as to the link between housing layout factors, solar radiation and courtyard space.

Following the chapter 3 which develops a series of simple theoretical model of courtyard housing layout, this chapter is seen as a pilot study which reports a basic relationship between the parametric variations of the housing layout factors and a series of its corresponding usable courtyard areas. To investigate this, firstly, a range of Courtyard area ratio (CAR) together with building coverage (BC) and floor area ratio (FAR) which corresponds to the variations in the factors are identified. Secondly, the amounts of solar radiation recorded on the range of courtyard building facades of the courtyard areas are calculated using the selected computer programs, i.e. ICON and SHADEN. Thirdly, the relative relations of solar radiation to a range of the housing layout are then analysed on a seasonal basis. Lastly, brief descriptions for each housing layout factor and its ranges that make most use of utilising solar radiation based on each housing storey are given. The scopes of variations in solar radiation are expressed graphically the relative importance of the housing layout factors to conflicting requirements, density and solar access, in urban environment.

ABBREVIATIONS

Ac, net courtyard area per dwelling (m^2);

Ap, net plot area, excluding half road-width (m^2);

Ag, ground area of housing building (m^2);

BC, housing building coverage ratio;

FAR, floor area ratio;

CAR, courtyard area ratio;

ns, number of storeys;

Sr, setback space towards front road in the plot area Ap (m);

Sn, setback space towards due north in the plot area Ap (m);

t, the proportion of Ap to total plot area including allocations for community facilities;

f, net plot frontage to front road (m);

x_0, net plot depth (m);

x_1-x_i, plot depth of corresponding land-use allocation for community facilities (m);

dc, net courtyard frontage in courtyard dimension;

fc, net courtyard depth in courtyard dimension;

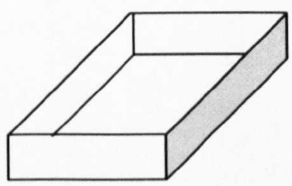
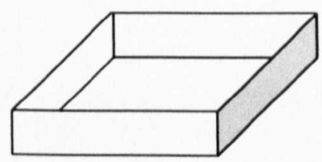
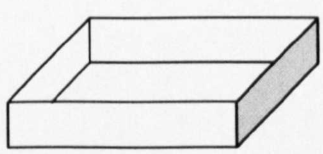
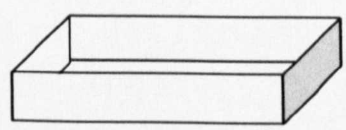
$d_{c.max}$, maximum depth in courtyard dimension;

$f_{c.max}$, maximum frontage in courtyard dimension;

SOL, direct solar radiation (GJ/sq.m);

5-1-2. Guidelines of courtyard housing model study

As outlined in the first section of this chapter, a series of Tables and corresponding Figures for the relationship of the variations of net courtyard area (Ac) and net plot area (Ap) to the ranges of the housing layout factors is presented. The results are produced, using the algebraic expressions developed from the three types of housing plot location.

Type I	Type II
	
fc = 9.61 m, dc = 12.42 m	fc = 11.41 m, dc = 10.46
Type III	Type IV
	
fc = 13.2, dc = 9.04	fc = 15, dc = 7.96

* allocated net plot area (Ap) = 201.25 m^2

allocated net ocurtyard area (Ac) = 119.36 m^2

Figure 5-1. The set of four courtyard plan dimensions whose frontage lies between 9.19 and 15 m and depth lies between 7.96 and 12.42 m for housing density of 40 units/hectare for one storey with street layout running E-W

There are four types of Tables allocated in each section to illustrate the relationship between varying the housing layout factor and its corresponding CAR, solar radiation and the aspect ratio of courtyard dimension.

1. The first table of each section explains a range of values for courtyard area (Ac), plot area (Ap), building coverage (BC) and floor area ratio (FAR) corresponding to the housing layout factors is produced to define courtyard area ratio (CAR).

2. The second table indicates the maximum ranges of the courtyard dimension to plot frontage ($f_{c.max}$) and depth ($d_{c.max}$) based on Ac and Ap as well as introducing other parameters such as setback spacing (S), plot frontage (f) and plot depth (x) according to the three types of housing plot location.

3. In order to illustrate the effects of the housing layout factors on the amounts of direct solar radiation falling in the courtyard facades, each shape corresponding to the variations of the housing layout factors, was simulated with the computer program combining its smallest and largest plan dimension within an allocated plot and courtyard area. However it is not possible to give an analyses based on all the possible combinations of the plan dimension for the allocated area. Therefore, four plan dimensions representing the range of the combination are selected and simulated, producing the maximum and minimum values of solar radiation for both summer and winter, which are tabulated in the third table. Figure 5-1 illustrates some examples of three-dimensional models for the modelling procedure. The examples of courtyard dimensions indicate usable courtyard frontage and depth for allocated Ap and Ac for housing density of 40 units/hectare shown in Table 5-2.

4. The last table shows a range of the aspect ratio of the courtyard dimensions resulted from variations in the housing layout factors.

5-2. One-storey: 3.7 m

Prior to comparing CAR and solar radiation with varying the housing layout factor, it is the assumption that the road width (r) faced by the frontage of each house plot is 5.5 m which is derived from the base value expressed in Table 3-15 of Section 3-3-2-3. For one-storey housing being 3.7m in height, setback spacings between the building and plot boundaries are calculated 0 and 1m to the front road and due north direction respectively from the equation 7a, 7b and 7c in chapter 3. The ground area of 66.89m^2 which excludes area for storage space (Essex council, 1973) is assumed based on occupancy of four people per unit for the courtyard housing.

As the aim of the study was to make the parametric and comparative analyses of the housing layout factors, a setback spacing to be considered in the house plot due to adjacent buildings, which is provided by city ordinances, is not taken into consideration. It is assumed that mutual consent between the plots is given in order to maximise the plot-use.

5-2-1. Housing Density (housing layout with parallel street E-W with frontage to the south)

An investigation is conducted concerning the effect of plot size on CAR and solar radiation for one-storey housing by changing housing density factor from 30 to 50 units/hectare at intervals of 5 units/hectare. A base value of 500 units for housing development scale is introduced resulting in a range of t value from 0.962 to 0.977 (Table 3-14). A layout of house plot frontage of 15m facing parallel street E-W to the south is referred here as one of three case model with changing plot location.

Table 5-1. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	202.53	284.42	0.712
35 units/hectare (t=0.974)	155.15	237.04	0.655
40 units/hectare (t=0.97)	119.36	201.25	0.593
45 units/hectare (t=0.966)	91.53	173.42	0.528
50 units/hectare (t=0.962)	69.26	151.15	0.458

Table 5-2. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	202.53	155.15	119.36	91.53	69.26
Sr	0	0	0	0	0
Sn	1	1	1	1	1
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	17.96	14.8	12.42	10.56	9.08
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-3. Effect of housing density on courtyard coverage and solar radiation for 1-storey for housing layout running street E-W

		Summer min	Summer max	Winter min	Winter max
30	CAR	0.712			
units/ hectare	SOL	124.213	144.404	109.048	116.624
35	CAR	0.655			
units/ hectare	SOL	101.863	120.036	92.256	120.036
40	CAR	0.593			
units/hectare	SOL	85.446	100.738	95.258	78.470
45	CAR	0.528			
units/hectare	SOL	71.892	85.153	60.940	71.579
50	CAR	0.458			
units/hectare	SOL	60.939	71.579	54.054	67.262

The values for setback spacing (Sr and Sn) and t in equation 10 and 11a are replaced by the value produced by equation 7a, 7b and 7c, and suggested by Figure 3-14 respectively. Therefore given values for Ac and Ap, and making the necessary assumptions discussed above, it is possible to determine building coverage (BC), FAR (Floor area ratio), CAR (Courtyard area ratio) and their corresponding size and dimension of the courtyard ($f_{c.max}$, $d_{c.max}$) in accordance with changing the housing density.

Table 5-1 shows the ranges of Ac varying from 69.26 to 202.53 m^2 which correspond to Ap from 151.15 to 284.42m^2 as a result of decreasing the density factor. Accordingly, a set of rectangular courtyard plans, whose frontage and depth lie between available $f_{c.max}$ and $d_{c.max}$, and whose areas lie Ac and Ap corresponding to the density variation, is shown in Figure 5-3. This is also useful to provide information about corresponding courtyard form and shape relating to each housing layout factor variation, which is to be dealt in Section 6-2. The variation in Ap and Ac results in corresponding values of 0.235 – 0.443 and 0.458 – 0.712 for BC and CAR respectively. The change of CAR in percentage from the base case is about 25 % (0.254). As can be seen in Figure 5-2, in summer, solar radiation fluctuates between 71.58 and 144.4 GJ in maximum irradiation load, and 60.94 and 124.21 GJ in minimum irradiation load. In winter, the range of maximum solar radiation is from 67.26 – 116.62 GJ, while minimum solar radiation is from 54.05 – 109.05 GJ. Therefore, the increases of solar radiation to the base case are 63.27 - 72.82 GJ and for summer and 49.36 – 55 GJ for winter respectively. Table 5-4 shows a range of the courtyard plan dimension to parametric density variations taking account of the relationship between Ap and Ac based on Figure 5-3. The initial attempt is made here by suggesting four types of the courtyard dimension to density variations, ranging from 1:1.6 to 3.3:1 in aspect ratio on $f_{c.max} : d_{c.max}$

Table 5-4. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1.11 : 1	1.45 : 1	1.88 : 1	2.46 : 1	3.25 : 1
II	1 : 1.07	1.17: 1	1.46 : 1	1.82 : 1	2.27 : 1
III	1 : 1.29	1 : 1.08	1.09 : 1	1.27: 1	1.47 : 1
IV	1 : 1.59	1 : 1.41	1 : 1.29	1 : 1.22	1 : 1.19

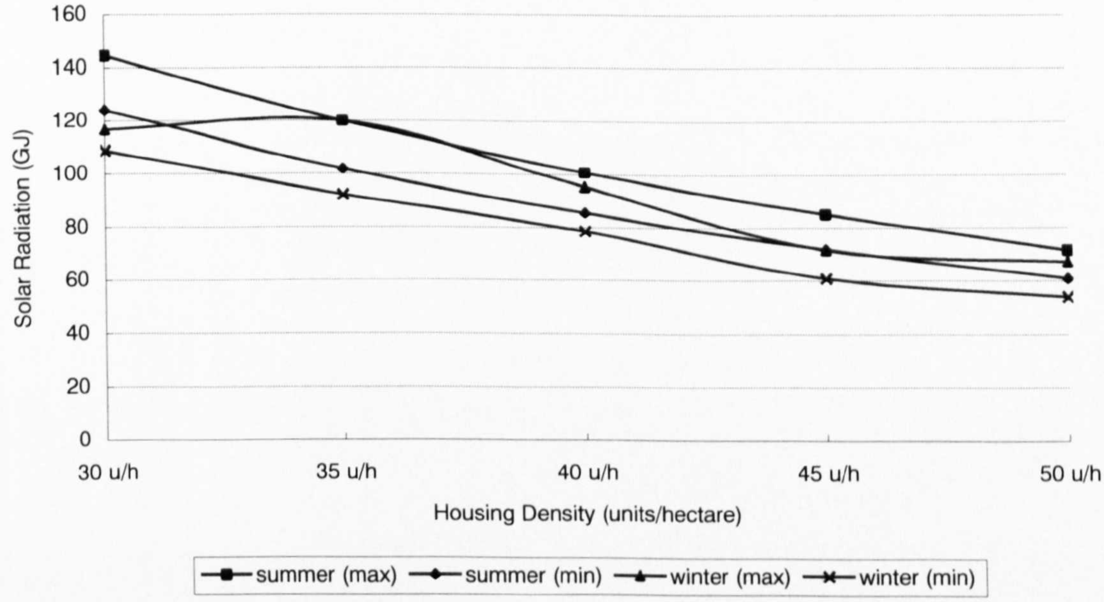


Figure 5-2. Solar radiation variations for one-storey housing in changing housing density factor in E-W street layout with plot frontage to the south direction

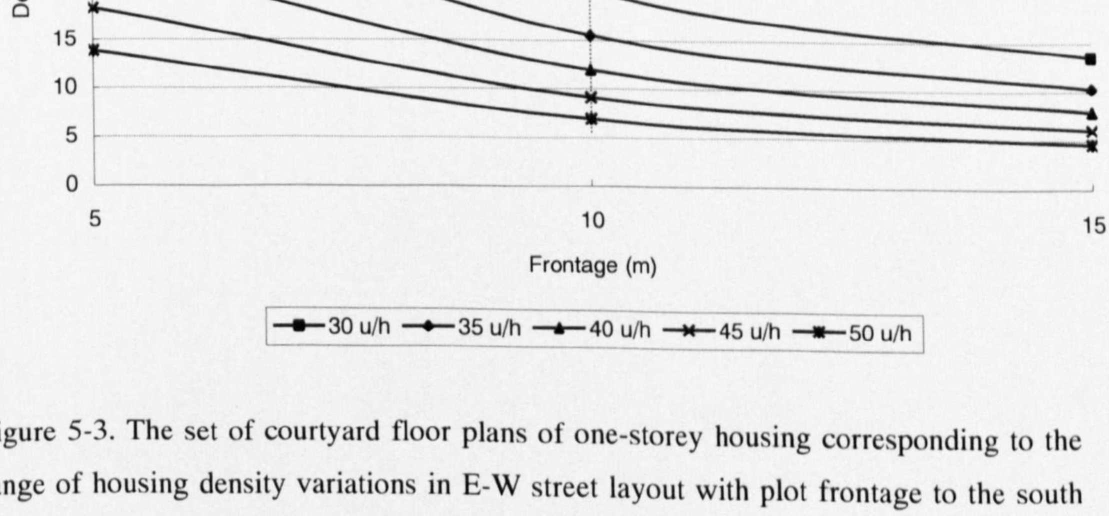


Figure 5-3. The set of courtyard floor plans of one-storey housing corresponding to the range of housing density variations in E-W street layout with plot frontage to the south direction

5-2-2. Plot dimension

In order to study the effect of changing plot dimension factor on CAR and solar radiation, the frontage of the housing plot is varied for one-storey housing taking values of 5, 10, 15, 20 and 25m. While a base value of 40 units/hectare for housing density and 0.97 for corresponding t are assumed, the other values are held as same as in the previous section on changing housing density factor (Table 3-14).

Table 5-5. Variation in plot use in terms of plot dimension

Plot dimension	Ac	Ap	CAR (Ac / A_p)
f = 5 m	156.86	228.75	0.686
f = 10 m	138.11	215	0.642
f = 15 m	119.36	201.25	0.593
f = 20 m	100.61	187.5	0.537
f = 25 m	81.86	173.75	0.471

Table 5-6. Plot depth for plot dimension and its corresponding courtyard dimension

Plot dimension	f = 5 m	f = 10 m	f = 15 m	f = 20 m	f = 25 m
Ap	228.75	215	201.25	187.5	173.75
Ac	156.86	138.11	119.36	100.61	81.86
Sr	0	0	0	0	0
Sn	1	1	1	1	1
f	5	10	15	20	25
X_0	45.75	21.5	13.42	9.38	6.95
$d_{c.max}$	44.75	20.5	12.42	8.38	5.95
$f_{c.max}$	5	10	15	20	25

Maximum dimension of courtyard in depth: $d_{c.max} = X_0 - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-7. Effect of plot dimension on courtyard coverage and solar radiation for 1-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
f = 5 m	CAR	0.686			
	SOL	187.695	222.011	99.727	108.864
f = 10 m	CAR	0.642			
	SOL	111.535	140.049	84.569	85.867
f = 15 m	CAR	0.593			
	SOL	83.600	100.932	78.592	95.098
f = 20 m	CAR	0.537			
	SOL	75.931	80.301	78.922	94.661
f = 25 m	CAR	0.471			
	SOL	67.906	74.967	75.393	80.732

A series of values for Ac and Ap is calculated using equation 10 and 11a in which the values of setback spacing from equation 7a, 7b and 7c along with the t value of 0.97 are replaced. The results of the variation of changing the plot frontage (f) facing parallel street E-W to the south are then presented in Table 5-5. Table 5-7 also indicates maximum and minimum solar irradiation for the ranges of the courtyard area ratio and size which courtyard dimensions are produced based on.

Table 5-5 shows the variation of net courtyard area (Ac) ranging from 81.86 to 156.86m^2 corresponding to the net plot area (Ap) of 173.75 – 228.75m^2 as the plot frontage reduces. Based on Ap and Ac, a set of rectangular courtyard plans lying between $f_{c.max}$ and $d_{c.max}$ according to the plot dimension variations is shown in Figure 5-4. Building coverage (BC) is within the ranges of 0.292 – 0.385. The values for CAR are from 0.471 – 0.686, which shows an increase of 22% (0.215) in CAR compared to the base case. The ranges of maximum values of solar irradiation for summer records are between 74.97 – 222.01 GJ and minimum between 67.91 – 187.7 GJ. In winter, maximum ranges of solar radiation are from 80.73 to 108.86 GJ, minimum ranges from 75.39 to 99.73 GJ. The increases of solar radiation compared to the base case are shown as 119.79–147.04 GJ for summer and 28.13 –24.33 GJ for winter respectively (Figure 5-4). Along with the variation in CAR, it seems to be obvious that changing plot frontage has an effect on the variations of the amounts of solar radiation. A range of the courtyard plan dimensions resulted from changing the plot frontage (f) are shown in Table 5-8. The four bands of the courtyard dimension corresponding to changing frontage produce the deviations of 7.65 – 12.75:1 in aspect ratio on $f_{c.max}$: $d_{c.max}$.

Table 5-8. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	f = 5	f = 10	f =15	f = 20	f = 25
I	1 : 6.27	1 : 1.38	1.88 : 1	3.98 :1	7.65 : 1
II	1 : 7.75	1 : 1.74	1.46 : 1	2.99 : 1	5.52 : 1
III	1 : 9.76	1 : 2.25	1.09 : 1	2.14 : 1	3.74 : 1
IV	1 : 12.75	1 : 3.04	1 : 1.29	1.43 :1	2.31 : 1

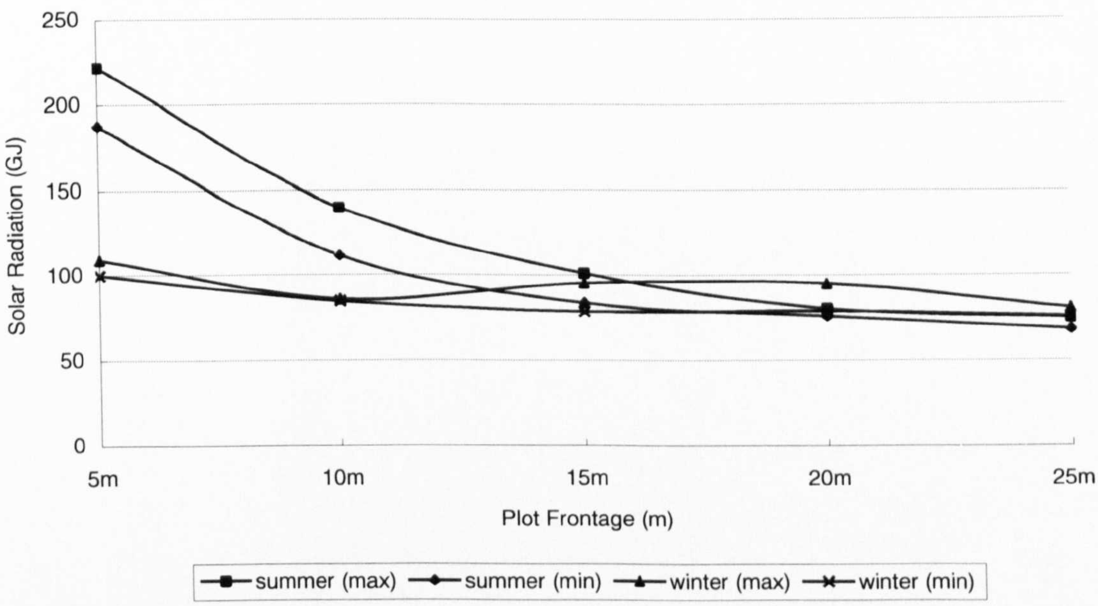


Figure 5-4. Solar radiation variations for one-storey housing in changing plot dimension factor in E-W street layout with plot frontage to the south direction

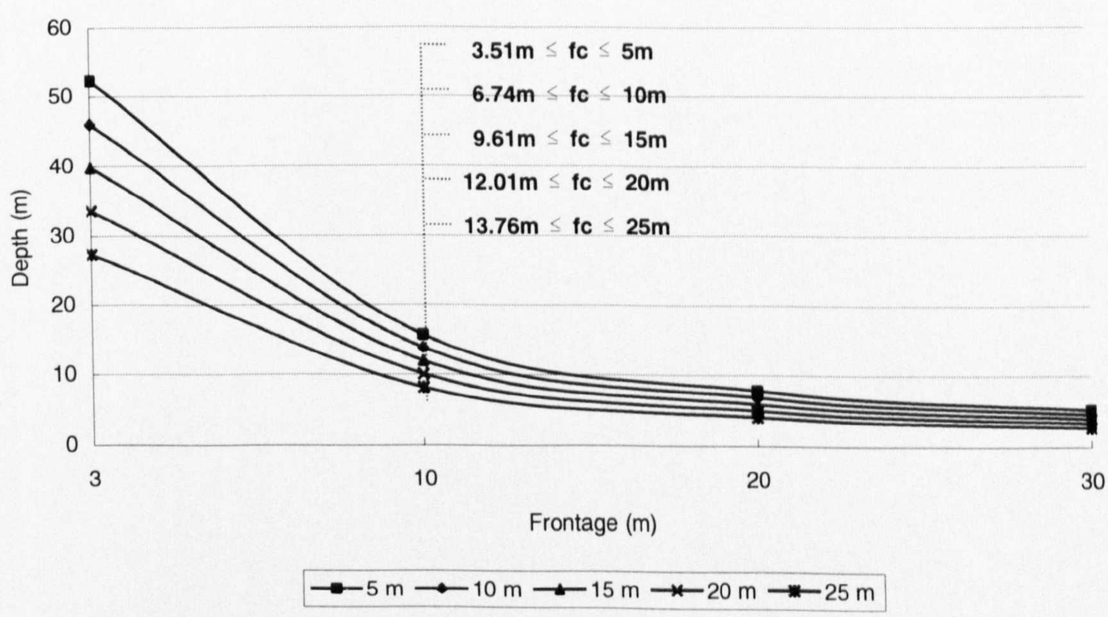


Figure 5-5. The set of courtyard floor plans of one-storey housing corresponding to the range of plot frontage variations in E-W street layout with plot frontage to the south direction

5-2-3. Housing Development Scale

A housing unit scale of 500 units for urban development was chosen in the previous sections to investigate the effect of the density and the plot dimension factors. In this section, to define the relationship to the housing development scale factor, CAR and solar radiation on one-storey housing in a layout of parallel streets E-W, the ranges of the housing unit scale are specified as 50, 100, 500, 1000 and 1500 units. The other values are held constant as 40 units/hectare is set for housing density and 15m for plot frontage.

Table 5-9. Variation in plot use in terms of housing development scale

Housing development scale	Ac	Ap	CAR (Ac / Ap)
50 units	117.86	199.75	0.59
100 units	117.86	199.75	0.59
500 units	119.36	201.25	0.593
1000 units	119.36	201.25	0.593
1500 units	118.86	200.75	0.592

Table 5-10. Plot depth for housing development scale and its corresponding courtyard dimension

Housing development scale	50 units	100 units	500 units	1000 units	1500 units
Ap	199.75	199.75	201.25	201.25	200.75
Ac	117.86	117.86	119.36	119.36	118.86
Sr	0	0	0	0	0
Sn	1	1	1	1	1
f	15	15	15	15	15
x_o	13.32	13.32	13.42	13.42	13.38
$d_{c.max}$	12.32	12.32	12.42	12.42	12.38
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Replacing t by 0.97 and setback spacing by 0 and 1 to the front road and due north in equation 10 and 11a, it is possible to observe the ranges of the values for Ac and Ap in terms of changing the factor on the layout. Accordingly, the corresponding values for the courtyard dimensions and solar radiation are shown in Table 5-9 and 11. As shown in Table 5-9, it can be seen that the variations of 117.86 and 118.86m² in Ac with increasing number of housing units are recorded.

Ap ranges from 199.75 and 200.75m^2. This shows a relatively small increase of about 0.2% in CAR compared to the base case when BC ranges 0.332-0.335 and CAR 0.59-0.592. Again, based on Ap and Ac, a set of rectangular courtyard plans according to the housing development scale variations is shown in Figure 5-6. As can seen in Figure 5-5, in summer, the maximum and the minimum solar radiation values are 100.13 –100.64 GJ and 84.61 – 85.48 GJ respectively in the courtyard recorded, resulting in the increase of about mere 0.5 – 0.87 GJ, which is relatively small compared to variations in the other factors, from the base case. The maximum values of 94.73 – 95.25 GJ and the minimum values of 77.95 – 78.59 GJ in solar radiation in winter produce the overall increase of 0.53 – 0.64 GJ. However, the variability for both CAR and solar radiation is small as a result of changing the scale of housing units in a development. Table 5-12 shows a range of the courtyard dimensions by changing the number of housing units in urban development. The aspect ratio of $f_{c.max} : d_{c.max}$ in the courtyard plan dimensions appears to range from 1.91:1 to 1:1.29.

Table 5-11. Effect of housing development scale on courtyard coverage and solar radiation for 1-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
50 units	CAR	0.59			
	SOL	84.612	100.132	77.951	94.726
100 units	CAR	0.59			
	SOL	84.612	100.132	77.951	94.726
500 units	CAR	0.593			
	SOL	85.477	100.834	78.591	95.254
1000 units	CAR	0.593			
	SOL	85.477	100.834	78.591	95.254
1500 units	CAR	0.592			
	SOL	85.477	100.834	78.591	95.254

Table 5-12. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	50 units	100 units	500 units	1000 units	1500 units
I	1.91:1	1.91:1	1.88:1	1.88:1	1.89:1
II	1.48:1	1.48:1	1.46:1	1.46:1	1.47:1
III	1.1:1	1.1:1	1.09:1	1.09:1	1.09:1
IV	1:1.29	1:1.29	1:1.29	1:1.29	1:1.29

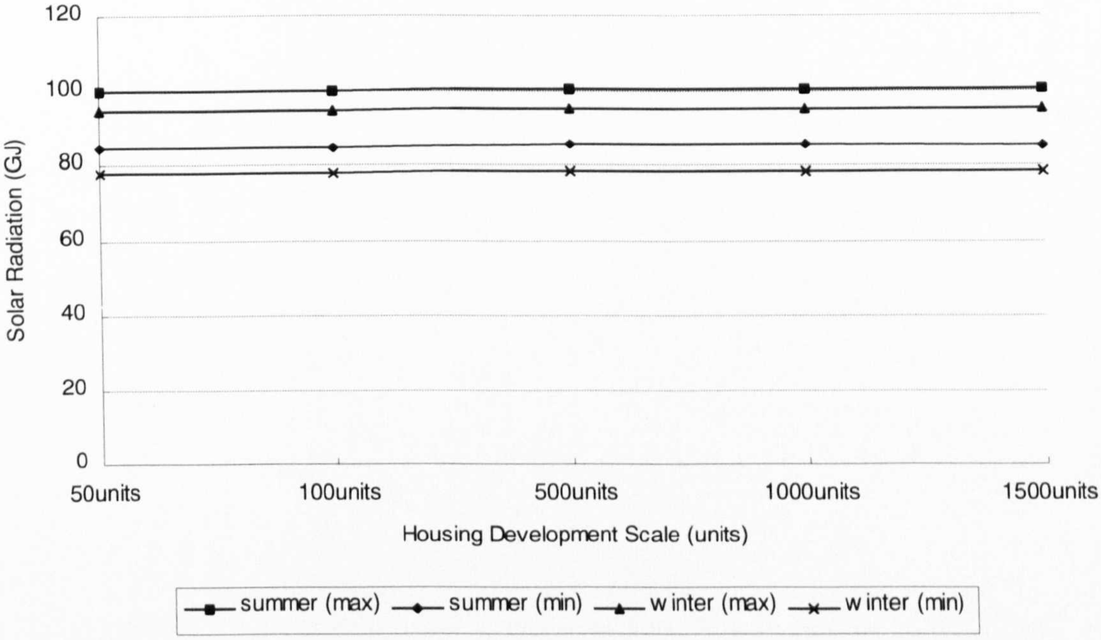


Figure 5-6. Solar radiation variations for one-storey housing in changing housing development scale factor in E-W street layout with plot frontage to the south direction

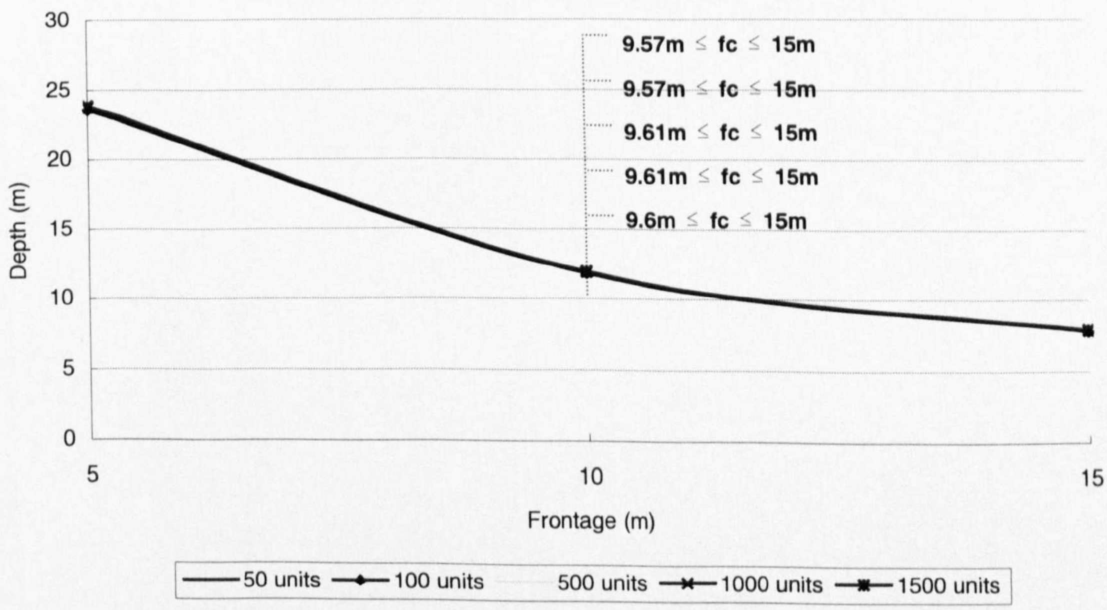


Figure 5-7. The set of courtyard floor plans of one-storey housing corresponding to the range of housing development scale variations in E-W street layout with plot frontage to the south direction

5-2-4. Housing orientation (housing layout with parallel street E-W with frontage to the north)

Since the application of setback spacing to housing plot can be altered depending on the location of the plot in E-W layout, the investigation has been carried out on a plot with the front road to north in E-W layout. To investigate the relation of density factor to CAR and solar radiation for one-storey housing, housing densities are changed from 30 to 50 units/hectare as in the case of plots with the front road to south. Housing development scale is assumed 500 units, resulting in t value from 0.962 – 0.977. The plot frontage width faced by the front road is 15m. Equation 10 and 11b are used, thereby producing the corresponding results of Ac and Ap to the parametric variation. The results for CAR and solar radiation are found in Table 5-13, 14 and 15.

Table 5-13. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	217.53	284.42	0.765
35 units/hectare (t=0.974)	170.15	237.04	0.718
40 units/hectare (t=0.97)	134.36	201.25	0.668
45 units/hectare (t=0.966)	106.53	173.42	0.614
50 units/hectare (t=0.962)	84.26	151.15	0.557

Table 5-14. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	217.53	170.15	134.36	106.53	84.26
Sr	0	0	0	0	0
Sn	0	0	0	0	0
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	18.96	15.8	13.42	11.56	10.08
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - Sn$ ($Sn \geq Sr$) or $X_o - Sr$ ($Sn \leq Sr$)
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

The ranges of Ac from 84.26 to 217.53 m^2 are presented in Table 5-13, whilst Ap varies from 151.15 to 284.42. Accordingly variations in CAR is 21% (0.208) which is somewhat lower than those of E-W layout with front road to south. A set of rectangular courtyard plans to the density variations for housing layout with frontage to the north is shown in Figure 5-9. The ranges of 80.67 – 151.84 GJ for maximum solar radiation and 68.47 – 131.33 GJ for minimum are observed in summer. This indicates an increase of 62.87 – 71.16 GJ from the base case. In winter, the maximum and the minimum solar radiation range 62.12 – 113.99 GJ and 78.32 – 120.54 GJ respectively, in which an increase of 42.22 – 51.86 GJ are recorded from the base case (Figure 5-8). Four types of the courtyard plan dimension corresponding to each density bands vary from 2.67:1 to 1:1.65 in aspect ratio on $f_{c.max} : d_{c.max}$

Table 5-15. Effect of housing density on courtyard coverage and solar radiation for 1-storey for housing layout running street N-S

		Summer		Winter	
		min	max	min	max
30	CAR	0.765			
units/ hectare	SOL	131.332	151.837	120.543	113.986
35	CAR	0.718			
units/ hectare	SOL	109.111	127.859	108.754	98.125
40	CAR	0.668			
units/hectare	SOL	92.462	108.918	99.253	84.637
45	CAR	0.614			
units/hectare	SOL	79.148	93.86	91.09	73.06
50	CAR	0.557			
units/hectare	SOL	68.465	80.673	78.323	62.124

Table 5-16. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1.03:1	1.32:1	1.67:1	2.11:1	2.67:1
II	1:1.14	1.09:1	1.32:1	1.6:1	1.94:1
III	1:1.36	1:1.15	1.01:1	1.17:1	1.33:1
IV	1:1.65	1:1.47	1:1.34	1:1.25	1:1.21

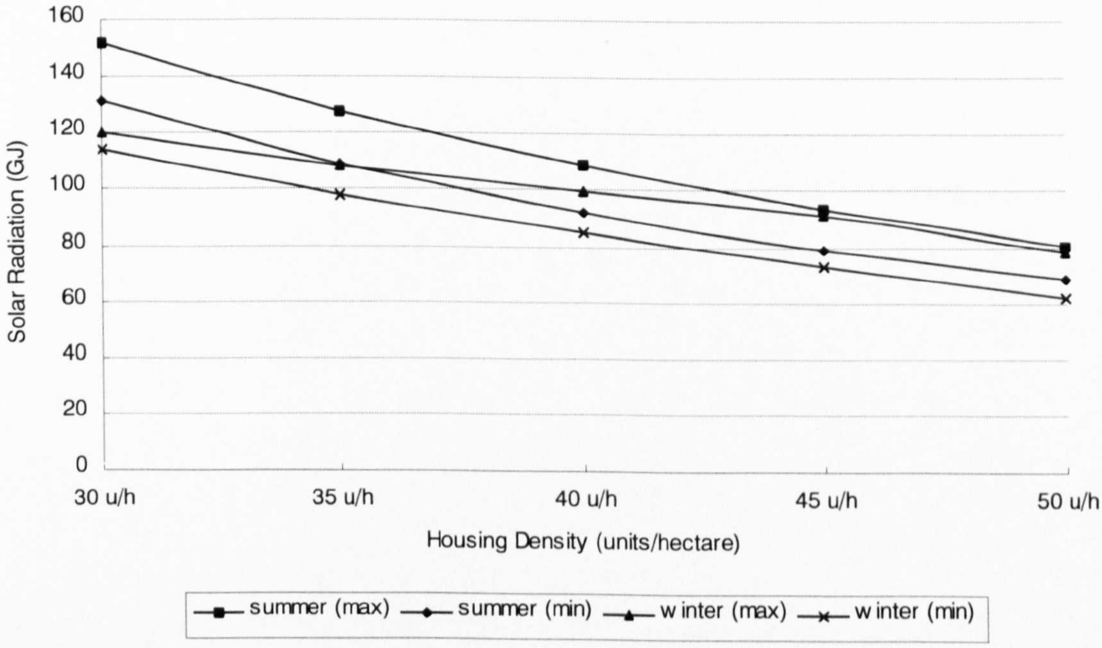


Figure 5-8. Solar radiation variations for one-storey housing in changing housing density factor in E-W street layout with plot frontage to the north direction

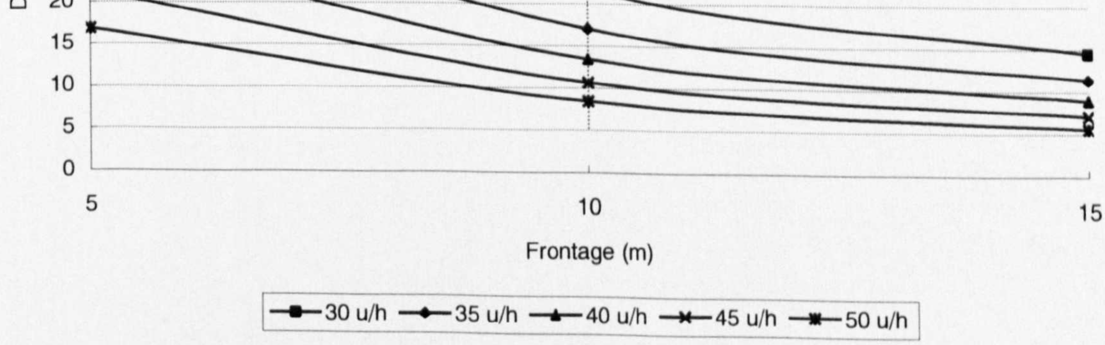


Figure 5-9. The set of courtyard floor plans of one-storey housing corresponding to the range of housing density variations in E-W street layout with plot frontage to the north direction

5-2-5. Housing Orientation (housing layout with parallel street N-S)

The size of useable courtyard area inside housing can be also determined by the way of orientating housing plot to front road. As the distances for the setback spacing in housing plot between the boundaries of building and plot are varied with placing front road to the plot, it can be typically divided into two types of parallel street running E-W and N-S.

Table 5-17. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	198.57	284.42	0.698
35 units/hectare (t=0.974)	154.35	237.04	0.651
40 units/hectare (t=0.97)	120.94	201.25	0.601
45 units/hectare (t=0.966)	94.97	173.42	0.548
50 units/hectare (t=0.962)	74.18	151.15	0.491

Table 5-18. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	198.57	154.35	120.94	94.97	74.18
Sr	0	0	0	0	0
Sn	1	1	1	1	1
f	15	15	15	15	15
x_0	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	18.96	15.8	13.42	11.56	10.08
$f_{c.max}$	14	14	14	14	14

Maximum dimension of courtyard in depth: $d_{c.max} = X_0 - Sr$
Maximum dimension of courtyard in frontage: $f_{c.max} = f - Sn$

Here, in order to find out relative benefits of locating housing plot to the front road in terms of solar access, the effects of changing the density factor on a layout with parallel street N-S are examined. As in the case of E-W, the values of the housing density are altered from 30 to 50 units/hectare. The number of 500 units in the housing development is assumed to be with the plot frontage of 15m. Others variables are held constant as usual. Equation 10 and 11c are introduced to calculate Ac and Ap using a series of t values defined in Table 3-14 and replacing the values for the setback spacing from equation from 7a, 7b and 7c for the case study on the layout. Then, the ranges of corresponding CAR (Table 5-17) and solar radiation (Table 5-19) to Ap and Ac are identified for both summer and winter.

Table 5-19. Effect of housing density on courtyard coverage and solar radiation for 1-storey for housing layout running street N-S

		Summer		Winter	
		min	max	min	max
30	CAR	0.698			
units/ hectare	SOL	112.599	125.645	113.314	129.700
35	CAR	0.651			
units/ hectare	SOL	100.163	116.523	93.395	107.609
40	CAR	0.601			
units/hectare	SOL	88.674	108.061	77.820	89.752
45	CAR	0.548			
units/hectare	SOL	77.975	99.381	64.569	75.503
50	CAR	0.491			
units/hectare	SOL	67.965	90.260	53.680	63.295

The ranges in Ac vary from 74.18 to 198.57 which appear to be a smaller range than the E-W layout corresponding to Ap of 151.15 – 284.42 with decreasing the housing density. A set of rectangular courtyard plans to the density variations for N-S layout is shown in Figure 5-10. This results in CAR range of 0.491 – 0.698 showing the increase of 21% compared to the base case. Figure 5-10 indicates the maximum and the minimum solar radiation recorded in summer being 90.26 – 125.64 GJ and 67.96 – 112.6 GJ respectively. This indicates an increase of 35.39 - 44.63 GJ compared to the base case. In winter, the maximum and the minimum solar radiation received are 63.3 – 129.7 GJ and 53.68 – 113.31 GJ respectively, showing an overall increase of 59.63 - 66.41 GJ.

The ranges of courtyard dimension to the variations in the housing density factor in N-S layout are shown in Table 5-20, illustrating four courtyard aspect ratio to each density variation and ranging between 2.64:1 – 1:1.81.

Table 5-20. Ratio of shapes for courtyard dimensions corresponding to parametric variations

(aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1:1.01	1.27:1	1.62:1	2.06:1	2.64:1
II	1:1.21	1.03:1	1.26:1	1.53:1	1.87:1
III	1:1.47	1:1.24	1:1.06	1.08:1	1.24:1
IV	1:1.81	1:1.62	1:1.49	1:1.41	1:1.37

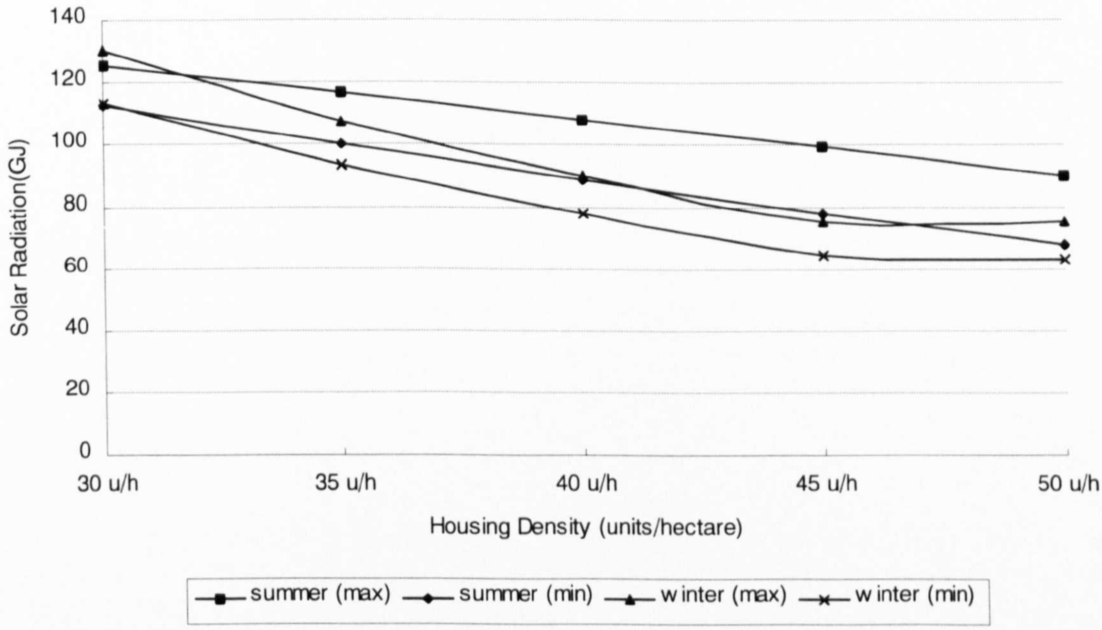


Figure 5-10. Solar radiation variations for one-storey housing in changing housing density factor in N-S street layout with plot frontage to both the east and the west direction

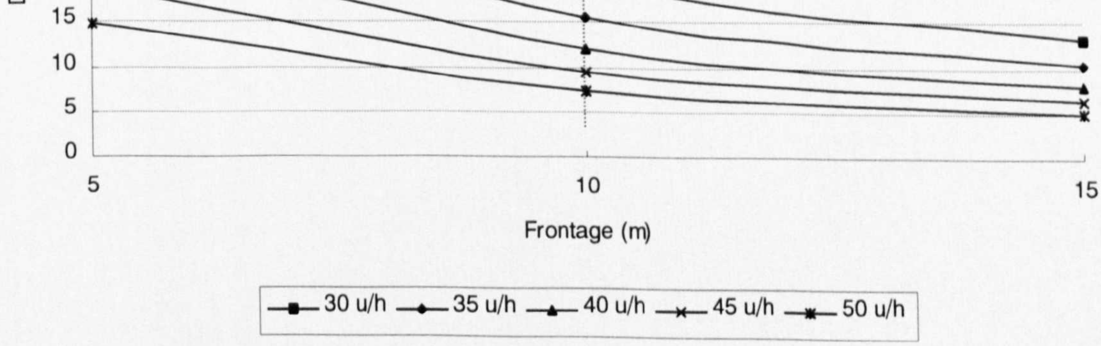


Figure 5-11. The set of courtyard floor plans of one-storey housing corresponding to the range of housing density variations in N-S street layout with plot frontage to both the east and the west direction

5-3. Two-storey: 6.4 m (3.7 + 2.7)

In this study, to find out the effect of varying the housing layout factors on the range of courtyard sizes and dimensions in terms of changing building height, it is decided to analyse comparatively the variations of CAR and solar radiation in two-storey housing. Hence the setback spacing required to meet the current building regulation code for the two-storey housing between the boundaries are proposed as 0 and 2m to the front road (Sr) and due north (Sn) respectively (Equation 7a, 7b and 7c). The other values made in the assumption for the simulation are indicated below depending upon each condition.

5-3-1. Housing Density (housing layout with parallel street E-W with frontage to the south)

Table 5-21. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	187.53	284.42	0.659
35 units/hectare (t=0.974)	140.15	237.04	0.591
40 units/hectare (t=0.97)	104.36	201.25	0.519
45 units/hectare (t=0.966)	76.53	173.42	0.441
50 units/hectare (t=0.962)	54.26	151.15	0.359

The investigation has been carried out to examine the effect of plot size on CAR and solar radiation for two-storey housing with increasing housing density from 30 to 50 units/hectare leaving 5 units per hectare between parametric variations as 30, 35, 40, 45 and 50 units/hectare. The base value of 500 units for number of housing units for the development scale used in the simulation on the layout with E-W street are again applied (Table 3-14).

Table 5-22. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	187.53	140.15	104.36	76.53	54.26
Sr	0	0	0	0	0
Sn	2	2	2	2	2
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	16.96	13.8	11.42	9.56	8.08
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-23. Effect of housing density on courtyard coverage and solar radiation for 2-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
30	CAR	0.659			
units/ hectare	SOL	186.747	212.404	145.589	161.737
35	CAR	0.591			
units/ hectare	SOL	149.855	171.102	118.477	132.175
40	CAR	0.519			
units/hectare	SOL	123.019	138.466	94.962	101.127
45	CAR	0.441			
units/hectare	SOL	101.261	110.929	71.725	74.685
50	CAR	0.359			
units/hectare	SOL	84.287	86.701	51.654	51.919

Sr and Sn based on considering two-storey height and t value (Table 3-14) are introduced to equation 10 and 11a. Using Ac and Ap along with the other necessary assumption made, CAR and its corresponding aspect ratio ($f_{c.max}$: $d_{c.max}$) are produced in terms of the courtyard size and dimension (Table 5-21, 22). Therefore the variations of solar radiation are identified (Table 5-23).

The range of Ac is between 54.26 and 187.53, while the range of 151.15 –

284.42 in Ap is held constant as in the case of varying the density factor on one-storey housing. A set of rectangular courtyard plans whose dimensions and areas correspond to the density variation is also shown in Figure 5-13 for two-storey housing. The corresponding BC and CAR are 0.235-0.443 and 0.359-0.659, an increase of 30%, which is 5% greater than one-storey case in CAR variations, compared to the base case. As can be seen in Figure 5-12, in summer, solar radiation range is recorded between 86.7 – 212.4 GJ in maximum and 84.29– 186.75 GJ in minimum. The fluctuations are higher and with wider ranges than those tabulated for one-storey housing. In this account, the increase of 102.46 - 125.7 GJ is marked compared to the base case in CAR. In winter, maxima of 51.92 – 161.74 GJ and minima of 51.65 – 145.59 GJ in solar radiation are indicated, again showing, in general higher and wider ranges than those for one-storey housing in overall density ranges excluding a high density band (50 units/hectare). An increase of 93.94–109.82 GJ is marked compared to the base case in solar radiation. Therefore, the results indicate that the range of increase of CAR and solar radiation in two-storey case becomes greater than lower storey as long as density changes in E-W layout is concerned. Table 5-24 shows the possible ranges of the courtyard plan dimension complying with changing density variations based on Figure 5-13. The ranges of 4.14:1 – 1:1.53 are shown in aspect ratio on $f_{c.max} : d_{c.max}$.

Table 5-24. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1.2:1	1.61:1	2.16:1	2.94:1	4.14:1
II	1:1	1.28:1	1.63:1	2.1:1	2.76:1
III	1:1.22	1:1.01	1.18:1	1.4:1	1.66:1
IV	1:1.53	1:1.36	1:1.25	1:1.19	1:1.2

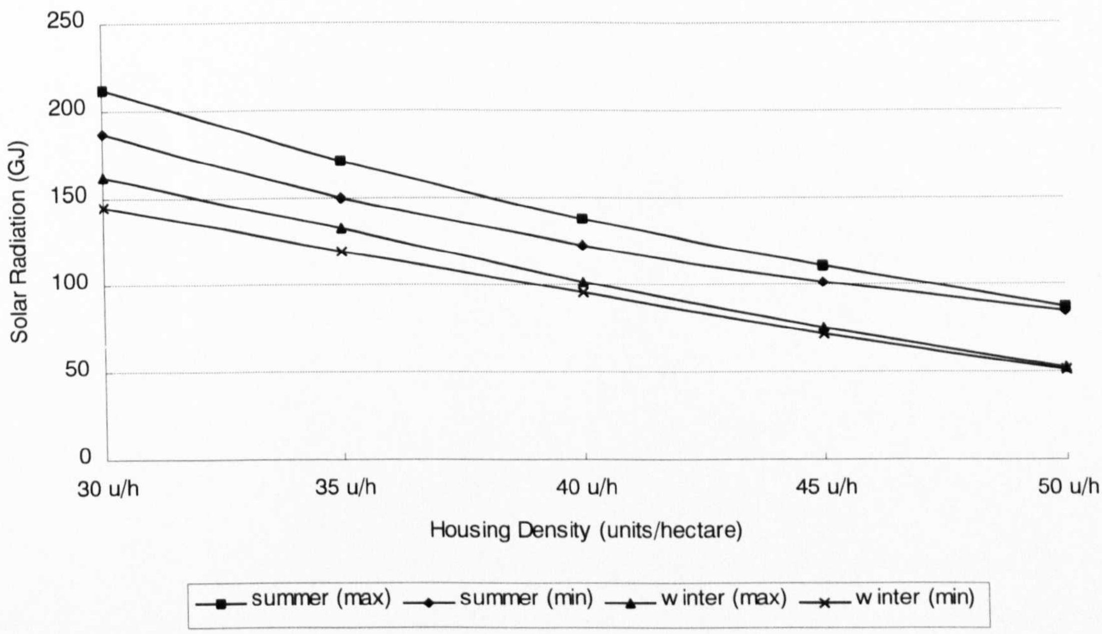


Figure 5-12. Solar radiation variations for two-storey housing in changing housing density factor in E-W street layout with plot frontage to the south direction

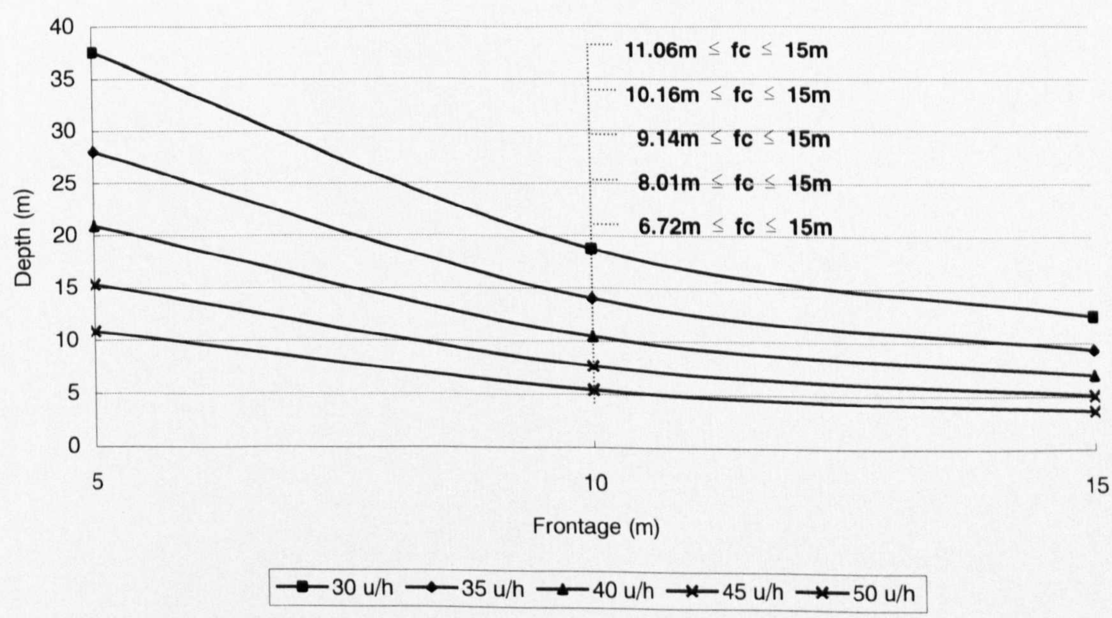


Figure 5-13. The set of courtyard floor plans of two-storey housing corresponding to the range of housing density variations in E-W street layout with plot frontage to the south direction

5-3-2. Plot Dimension

Table 5-25. Variation in plot use in terms of plot dimension

Plot dimension	Ac	Ap	CAR (Ac / Ap)
f = 5 m	151.86	228.75	0.664
f = 10 m	128.11	215	0.596
f = 15 m	104.36	201.25	0.519
f = 20 m	80.61	187.5	0.43
f = 25 m	56.86	173.75	0.327

The frontage (f) of the housing plot is changed between 5, 10, 15, 20 and 25m so as to analyse the effect of changing plot dimension on CAR and solar radiation on two-storey housing. The other values taken for the assumption such as housing density (40 units/hectare), t value (0.97) and housing development scale (500 units) are same as shown in plot dimension case for one-storey housing.

Table 5-26. Plot depth for plot dimension and its corresponding courtyard dimension

Plot dimension	f = 5 m	f = 10 m	f = 15 m	f = 20 m	f = 25 m
Ap	228.75	215	201.25	187.5	173.75
Ac	151.86	128.11	104.36	80.61	56.86
Sr	0	0	0	0	0
Sn	2	2	2	2	2
f	5	10	15	20	25
X_o	45.75	21.5	13.42	9.38	6.95
$d_{c.max}$	43.75	19.5	11.42	7.38	4.95
$f_{c.max}$	5	10	15	20	25

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-27. Effect of plot dimension on courtyard coverage and solar radiation for 2-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
f = 5 m	CAR	0.664			
	SOL	242.428	269.651	120.999	123.454
f = 10 m	CAR	0.596			
	SOL	159.127	187.142	103.683	111.638
f = 15 m	CAR	0.519			
	SOL	123.258	138.521	95.275	101.779
f = 20 m	CAR	0.43			
	SOL	106.983	108.948	76.537	77.125
f = 25 m	CAR	0.327			
	SOL	84.266	102.013	53.848	56.071

Table 5-27 shows the variations of solar radiation as expressed on a basis of Ac, Ap and CAR, which are produced by equation 10 and 11a. Table 5-25 indicates Ac ranges 56.86 – 151.86 m^2 with altering the plot frontage while Ap ranges from 173.75 to 228.75, which is in the same range as in the frontage variation of one-storey housing. A set of rectangular courtyard plans corresponding to the plot dimension variation for two storey housing is shown in Figure 5-15. The corresponding BC corresponding to Ac and Ap cover from 0.292 to 0.385 and CAR from 0.327 to 0.664, an increase of 34% CAR compared to the base case and resulting in an increase of 12% to the plot dimension case of one-storey. This clearly shows CAR variations caused by changing plot frontage are much greater than those by changing plot size, i.e. housing density on a basis of the same building height. Figure 5-14 shows that the ranges of maximum values of solar radiation for summer are 102.01 – 269.65 GJ and minimum being 84.27 – 242.43 GJ. This indicates an increases of about 27.04 – 47.6 GJ for the maximum and 16.3 – 54.7 GJ for the minimum to the one-storey case respectively, thereby implying an overall increase of solar radiation received as increasing building height from one to two-storey. An increase to the base case are recorded 158.16–167.64 GJ. In winter, maximum values of solar radiation are 56.07 – 123.45 GJ, minimum values ranging 53.85- 121 GJ. The differences of the maximum solar radiation are between –24.66 and +14.59 GJ and minimum being between –21.55 and +21.27. Thus the amounts of solar radiation are high in narrow frontage bands (5 - 15m) and low in relatively wide frontage band (20 – 25m), while the ranges of variations are high compared to those of one-storey case. An increase of 67.15 - 67.38 GJ are recorded compared to the base case. The four bands of the courtyard plan dimension corresponding to changing frontage produce aspect ratio of 11.01:1 – 1:12.61 on $f_{c.max}$: $d_{c.max}$ (Table 5-28).

Table 5-28. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	f = 5	f = 10	f =15	f = 20	f = 25
I	1:6.07	1:1.28	2.16:1	4.96:1	11.01:1
II	1:7.53	1:1.63	1.63:1	3.57:1	7.4:1
III	1:9.59	1:2.15	1.18:1	2.41:1	4.51:1
IV	1:12.61	1:2.97	1:1.25	1.48:1	2.32:1

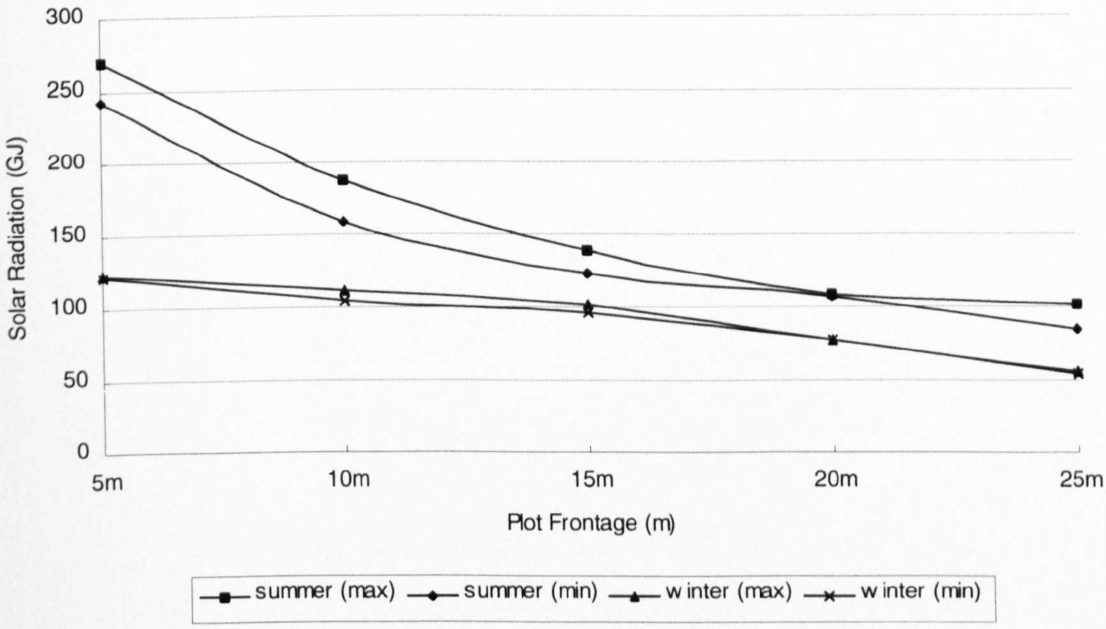


Figure 5-14. Solar radiation variations for two-storey housing in changing plot dimension factor in E-W street layout with plot frontage to the south direction

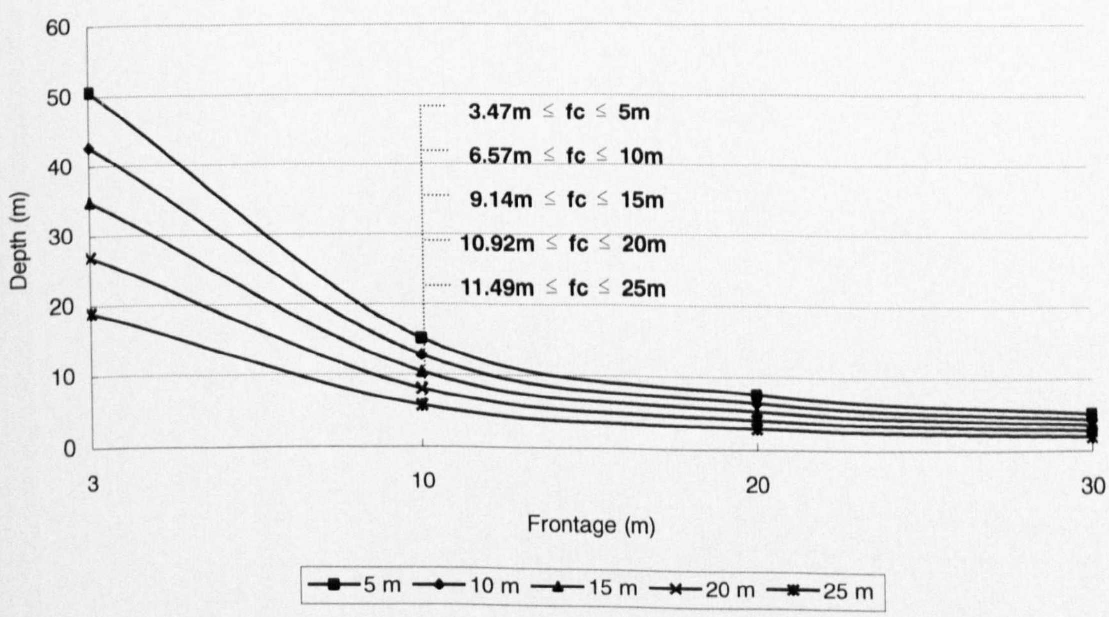


Figure 5-15. The set of courtyard floor plans of two-storey housing corresponding to the range of plot frontage variations in E-W street layout with plot frontage to the south direction

5-3-3. Housing Development Scale

The number of housing units in a development was varied using values of 50, 100, 500, 1000 and 1500 units to find out the relationship between the factor and two-storey courtyard housing, providing information on the variations of CAR and solar radiation with the other values held constant (D = 40units/hectare, f = 15m).

Table 5-29. Variation in plot use in terms of housing development scale

Housing development scale	Ac	Ap	CAR (Ac / Ap)
50 units	102.86	199.75	0.515
100 units	102.86	199.75	0.515
500 units	104.36	201.25	0.519
1000 units	104.36	201.25	0.519
1500 units	103.86	200.75	0.517

Table 5-30. Plot depth for housing development scale and its corresponding courtyard dimension

Housing development scale	50 units	100 units	500 units	1000 units	1500 units
Ap	199.75	199.75	201.25	201.25	200.75
Ac	102.86	102.86	104.36	104.36	103.86
Sr	0	0	0	0	0
Sn	2	2	2	2	2
f	15	15	15	15	15
x_o	13.32	13.32	13.42	13.42	13.38
$d_{c.max}$	11.32	11.32	11.42	11.42	11.38
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-31. Effect of housing development scale on courtyard coverage and solar radiation for 2-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
50 units	CAR	0.515			
	SOL	121.799	136.666	93.666	99.662
100 units	CAR	0.515			
	SOL	121.799	136.666	93.666	99.662
500 units	CAR	0.519			
	SOL	123.171	138.065	94.603	101.916
1000 units	CAR	0.519			
	SOL	123.171	138.065	94.603	101.916
1500 units	CAR	0.517			
	SOL	122.629	137.646	94.365	101.333

Table 5-29 contains data relating to Ap varying between 284.42 - 151.15m^2 and Ac between 102.86- 104.36m^2. Figure 5-17 also shows a set of rectangular courtyard plans to the housing development scale variation for two-storey housing. It shows a relatively small increase in BC and CAR ranging 0.332-0.335 and 0.515- 0.519 respectively, resulting in the increase of 0.4% in CAR. Accordingly there is a further increase of about 0.2% as compared to the housing development scale case with one-storey housing, which reflect only a slight increase in overall range. As can be seen in Figure 5-16, the maximum solar radiation in summer is in the ranges of 136.67 – 138.06 GJ recording a progressive increase of 36.53 – 37.43 GJ compared to the case of one-storey, minimum solar radiation is 121.8 – 123.17 GJ showing an increase of 37.19 – 37.69 GJ. In addition, an overall increase of 14.87– 14.89 GJ is shown as compared to the base case. In winter, the maximum ranges of 99.66 – 101.92 GJ and the minimum of 93.67 – 94.6 GJ are measured reaching the increase of 4.94-6.66 GJ and 15.71 – 16.01 GJ which is, on the whole, in much higher variations than the one-storey case. Compared to the base case, an increase of 5.99 – 7.31 GJ in solar radiation in winter is recorded. Therefore these results imply that, as the values of CAR decreases with increasing building height, the corresponding values of solar radiation increase. However, the effect of increasing housing units on the variations of CAR and solar radiation seems to be relatively small compared to the variations resulted from other housing layout factors. The ranges of the courtyard plan dimension bands by changing housing units are described in Table 5-32. Aspect ratios of 2.19:1 – 1:1.25 on $f_{c.max}$: $d_{c.max}$ are produced.

Table 5-32. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	50 units	100 units	500 units	1000 units	1500 units
I	2.19:1	2.19:1	2.16:1	2.16:1	2.17:1
II	1.65:1	1.65:1	1.63:1	1.63:1	1.64:1
III	1.19:1	1.19:1	1.18:1	1.18:1	1.18:1
IV	1:1.25	1:1.25	1:1.25	1:1.25	1:1.25

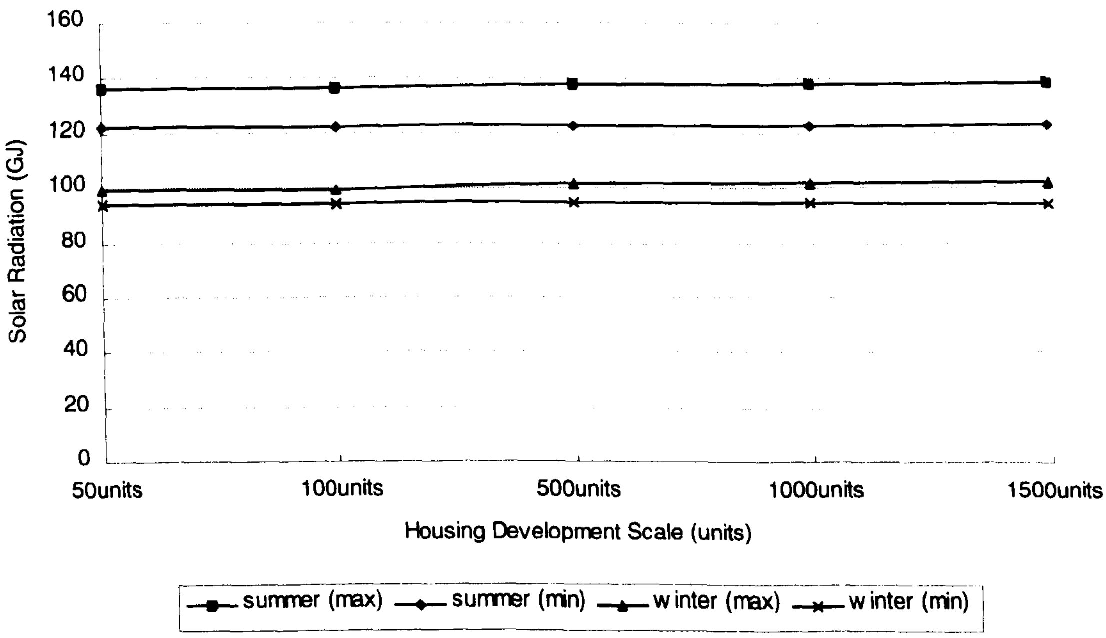


Figure 5-16. Solar radiation variations for two-storey housing in changing housing development scale factor in E-W street layout with plot frontage to the south direction

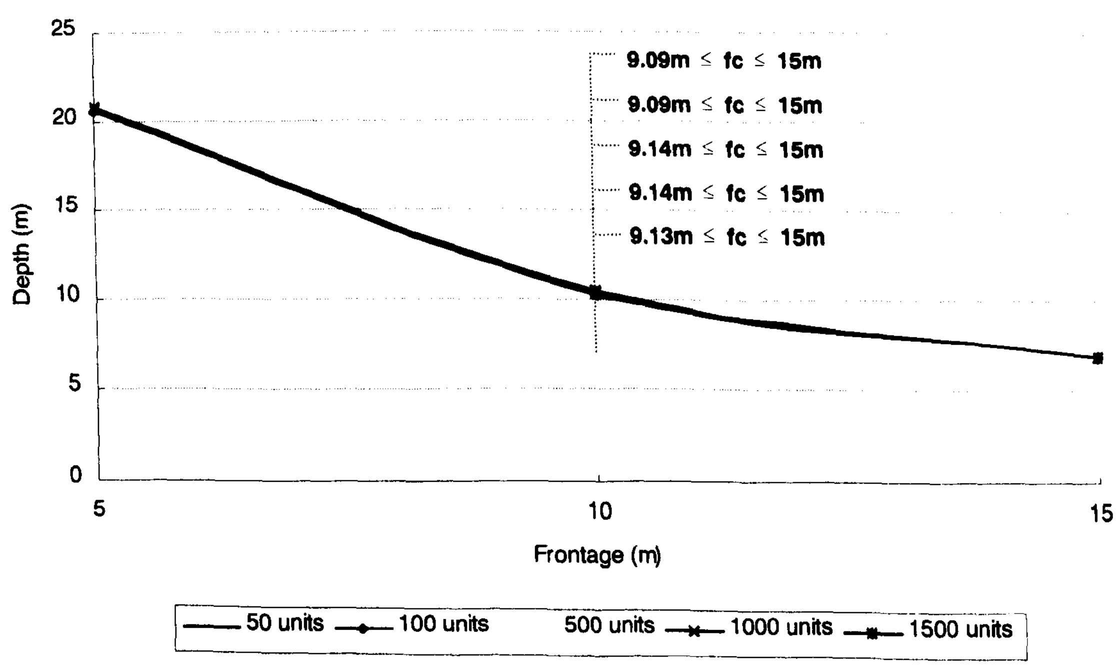


Figure 5-17. The set of courtyard floor plans of two-storey housing corresponding to the range of housing development scale variations in E-W street layout with plot frontage to the south direction

5-3-4. Housing Orientation (housing layout with parallel street E-W with frontage to the north)

The results of the effect of housing density on CAR and solar radiation for two-storey housing with plot facing parallel street E-W to the north appear to be same as those of one-storey housing. This is because setback spacings of the same distance are applied to housing models for both one and two-storey building under the assumption made in this study in accordance with the Korean-building regulation code.

5-3-5. Housing Orientation (housing layout with parallel street N-S)

Table 5-33. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	179.61	284.42	0.631
35 units/hectare (t=0.974)	138.55	237.04	0.585
40 units/hectare (t=0.97)	107.52	201.25	0.534
45 units/hectare (t=0.966)	83.41	173.42	0.481
50 units/hectare (t=0.962)	64.1	151.15	0.424

The ranges of the housing density factor are varied to investigate the effects of this factor on CAR and solar radiation in two-storey housing with the layout N-S with changing 30, 35, 40, 45 and 50 units/hectare. The ranges of CAR and solar radiation are calculated introducing equation 10 and 11c, replacing t by corresponding ranges to the densities, and Sr and Sn by 0 and 2 (Table 5-33, 34, 35)

Table 5-34. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	179.61	138.55	107.52	83.41	64.1
Sr	0	0	0	0	0
Sn	2	2	2	2	2
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	18.96	15.8	13.42	11.56	10.08
$f_{c.max}$	13	13	13	13	13

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - Sr$
Maximum dimension of courtyard in frontage: $f_{c.max} = f - Sn$

Table 5-35. Effect of housing density on courtyard coverage and solar radiation for 2-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
30	CAR	0.631			
units/ hectare	SOL	169.073	186.595	152.814	168.052
35	CAR	0.585			
units/ hectare	SOL	147.571	166.522	119.538	132.100
40	CAR	0.534			
units/hectare	SOL	127.834	147.317	94.336	103.540
45	CAR	0.481			
units/hectare	SOL	108.693	127.843	74.692	80.391
50	CAR	0.424			
units/hectare	SOL	91.874	108.205	58.469	61.588

Ap ranges from 151.15 to 284.42m² as appeared in the case of the layout E-W and Ac from 64.1 to 179.61m² by varying the housing density. A set of rectangular courtyard plans to the density variation for two-storey housing for N-S layout is shown in Figure 5-19. The ranges of CAR lies between 0.424- 0.631 with the result of a 21% increase compared to the base case, that is the same amounts of increase indicated in one-storey housing for E-W layout. Conversely, the effect of increasing building height on CAR is much less in N-S layout along with E-W layout with frontage to north than in E-W layout with frontage to south. Figure 5-18 clearly shows that, in summer, the maximum solar radiation ranges 108.2 – 186.6 GJ with an increase of 17.95 – 60.95 GJ to that of the one-storey case, the minimum being 91.87 – 169.07 GJ with change of 23.91 – 56.48 GJ showing a steady increase with increasing the height. Accordingly a change of the amounts of solar radiation in density variations become remarkable by comparison to lower storey case. An increase of 77.2 - 78.39 GJ is found compared to the base case. In winter, the maximum of 61.59 – 168.05 GJ and the minimum of 58.47 – 152.81 GJ are found, ranging from –1.71 to 38.35 for maximum, and from 4.79 to 39.5 GJ for minimum respectively, compared to the base case. This shows remarkable increases by means of decreasing the housing density compared to that of one-storey case. Especially, in the comparison of N-S layout and E-W layout, as housing density increases, the amounts of solar radiation of N-S layout become higher than those of E-W layout with plot frontage to south, and close to those of E-W layout to north. The change in winter solar radiation is between 94.35 - 106.46 GJ compared to the base case. The ranges of the courtyard plan dimension bands caused by changing the housing density for N-S layout are described in Table 5-36. The ranges of aspect ratio on $f_{c.max}$: $d_{c.max}$ lies between 2.64:1 and 1:1.68.

Table 5-36. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1:1.06	1.22:1	1.57:1	2.02:1	2.64:1
II	1:1.29	1:1.03	1.2:1	1.47:1	1.82:1
III	1:1.59	1:1.34	1:1.15	1:1	1.15:1
IV	1:2	1:1.8	1:1.68	1:1.6	1:1.58

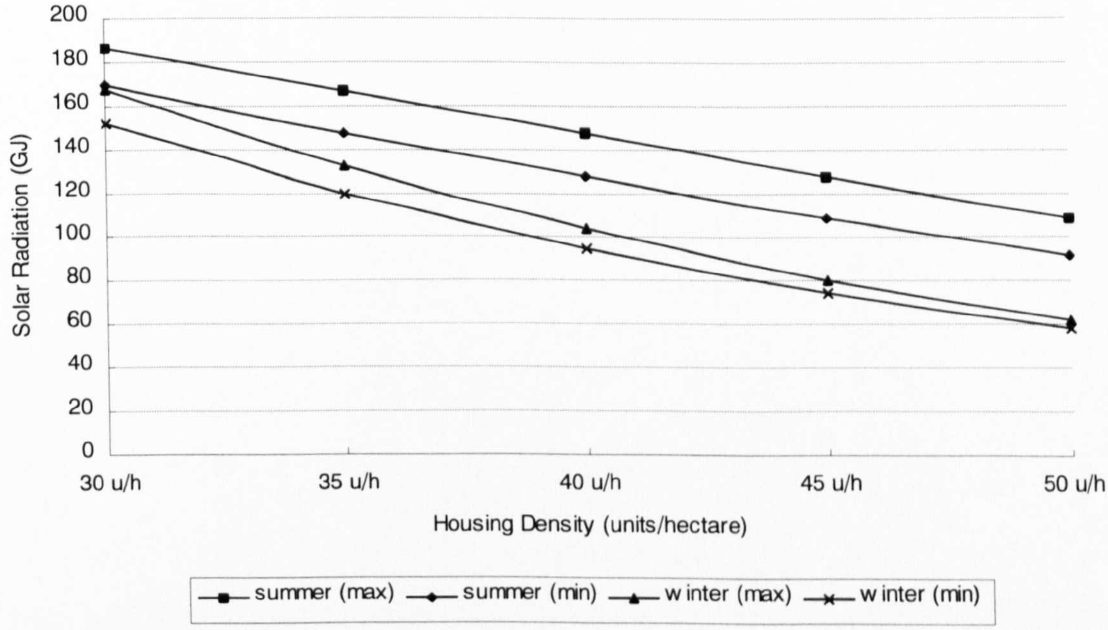


Figure 5-18. Solar radiation variations for two-storey housing in changing housing density factor in N-S street layout with plot frontage to both the east and the west

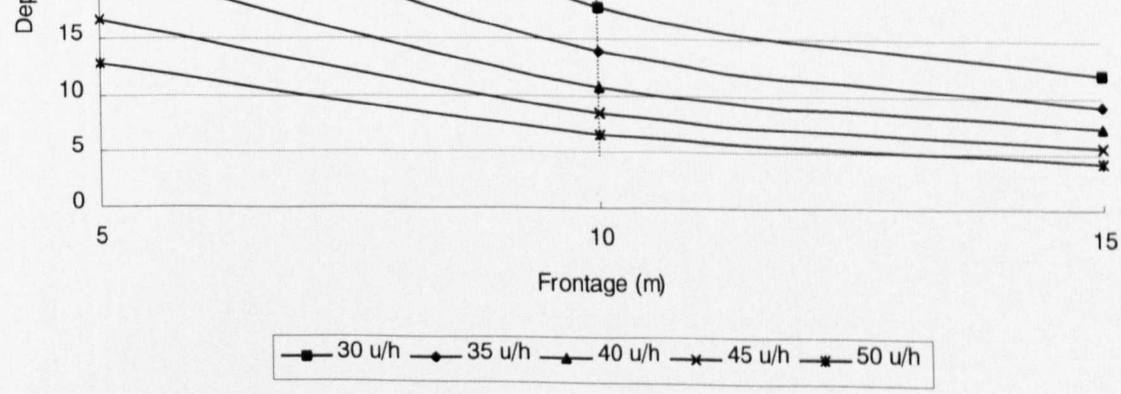


Figure 5-19. The set of courtyard floor plans of two-storey housing corresponding to the range of housing density variations in N-S street layout with plot frontage to both the east and the west direction

5-4. Three-storey: 9.1 m (6.4+2.7)

The parametric and comparative analyses on the effect of varying the housing layout factors on CAR and solar radiation are carried out for three-storey courtyard housing. Therefore setback spacing is set at 0.56m to front road (Sr) and 4.55m to due north (Sn) by using equation 7a, 7b and 7c to indicate that the effect of the application of the building code on the spacing become greater in three-storey housing. The other assumptions remain the same as with one and two-storey housing.

5-4-1. Housing Density (housing layout with parallel street E-W with frontage to the south)

The effect of the housing density factor on CAR and solar radiation for three-storey housing in E-W layout with frontage to south are found by altering between 30, 35 40, 45 and 50 units/hectare is analysed by defining the corresponding ranges of Ap, Ac (Table 5-37, 39).

Table 5-37. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	140.88	284.42	0.495
35 units/hectare (t=0.974)	93.5	237.04	0.394
40 units/hectare (t=0.97)	57.71	201.25	0.287
45 units/hectare (t=0.966)	29.88	173.42	0.172
50 units/hectare (t=0.962)	7.61	151.15	0.05

Table 5-38. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	140.88	93.5	57.71	29.88	7.61
Sr	0.56	0.56	0.56	0.56	0.56
Sn	4.55	4.55	4.55	4.55	4.55
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	13.85	10.69	8.31	6.45	4.97
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-39. Effect of housing density on courtyard coverage and solar radiation for 3-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
30	CAR	0.495			
units/ hectare	SOL	196.103	213.865	132.951	136.662
35	CAR	0.394			
units/ hectare	SOL	148.064	156.420	90.024	90.770
40	CAR	0.287			
units/hectare	SOL	107.218	111.249	55.200	56.881
45	CAR	0.172			
units/hectare	SOL	63.484	69.202	28.487	30.931
50	CAR	0.05			
units/hectare	SOL	20.328	27.037	10.199	10.254

Table 5-37 shows, while Ap remains the same as for one and two-storey housing, Ac ranges between 7.61 and 140.88m². A set of rectangular courtyard plans corresponding to the density variation for three-storey housing is shown in Figure 5-21. CAR ranges between 0.05 and 0.495 which indicate an overall increase of 45% compared to the base case. This seems to be remarkable compared to 25% for one-storey and 0.3% for two-storey housing, so that effect of changing housing density on CAR is the greatest in three-storey case. As can be seen from Figure 5-20, solar radiation in summer shows maximum ranges of 27.04 – 213.87 GJ, which records differences of 1.46 – 59.66 GJ in comparison with the two-storey case. Minimum ranges of 20.33 - 196.1 GJ are recorded showing the differences of –63.96 and 9.36 GJ compared to the same case, implying the change of solar radiation occurs so significantly especially in low housing density bands, when changing housing density, that the amounts of solar radiation of three storey exceeds those of lower storeys. The amounts of solar radiation become lower than lower-storey cases. In addition, there is an increase of 175.78 –186.83 GJ in solar radiation compared to the base case. In winter, maxima of 10.25 – 136.66 GJ show deviations of –41.66 and –25.07 compared to two-storey case and minima of 10.2 – 132.95 GJ deviating between –41.46 and 12.64 GJ showing similar variations as in summer. To sum up, it is noticeable that the higher the building storey is, the greater the effect of increasing the amounts of solar radiation becomes when increasing plot size. Thus this results in higher value of solar radiation in three-storey case than one and two-storey case in low density band, i.e.30 units/hectare. The ranges of the courtyard plan dimension in line with changing density variations are indicated in Table 5-40. The ranges of 29.41:1 – 1:3.25 are shown as aspect ratio on $f_{c.max}$: $d_{c.max}$.

Table 5-40. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1.6:1	2.41:1	3.9:1	7.54:1	29.41:1
II	1.27:1	1.78:1	2.62:1	4.46:1	14.6:1
III	1:1.02	1.26:1	1.6:1	2.18:1	4.78:1
IV	1:1.36	1:1.22	1:1.2	1:1.39	1:3.25

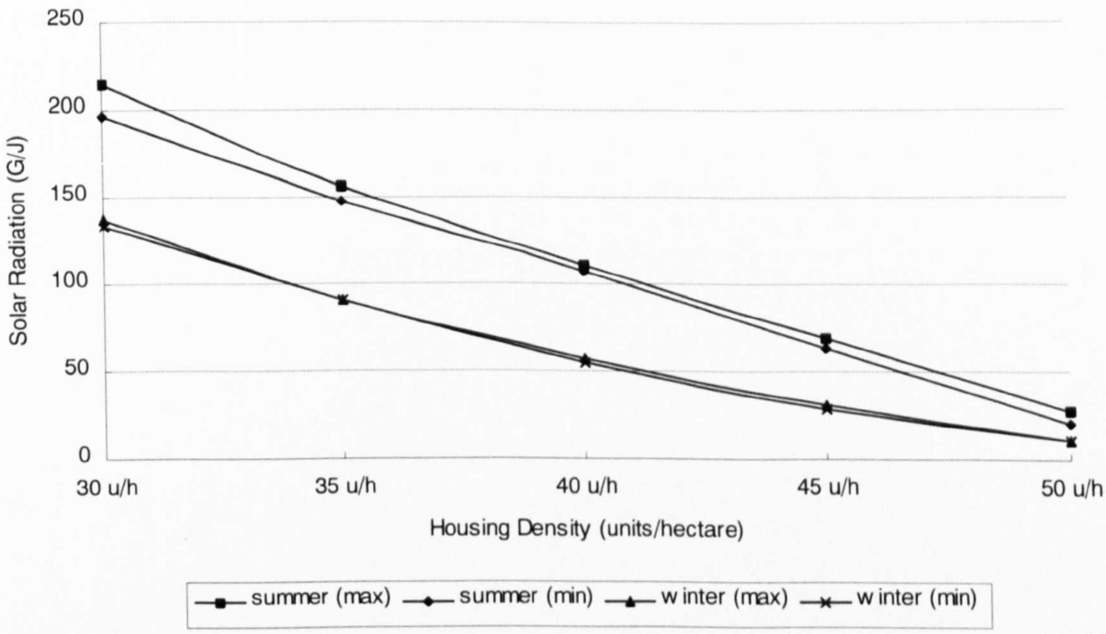


Figure 5-20. Solar radiation variations for three-storey housing in changing housing density factor in E-W street layout with plot frontage to the south direction

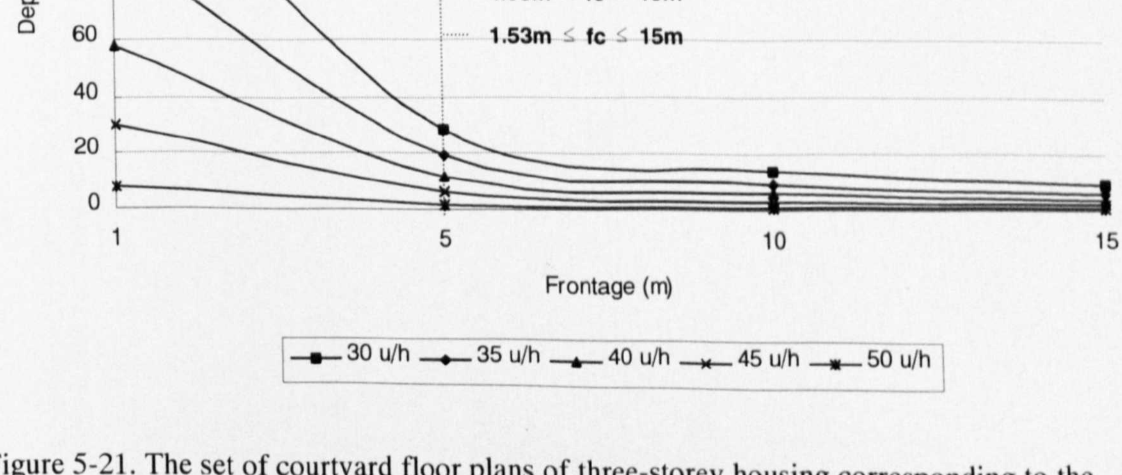


Figure 5-21. The set of courtyard floor plans of three-storey housing corresponding to the range of housing density variations in E-W street layout with plot frontage to the south direction

5-4-2. Plot dimension

Table 5-41. Variation in plot use in terms of plot dimension

Plot dimension	Ac	Ap	CAR (Ac / Ap)
f = 5 m	136.31	228.75	0.596
f = 10 m	97.01	215	0.451
f = 15 m	57.71	201.25	0.287
f = 20 m	18.41	187.5	0.098
f = 25 m	-20.89	173.75	-

With the changes of the plot frontage, taking values of 5, 10, 15, 20 and 25 m, the ranges of the values of CAR and solar radiation on three-storey house are indicated in Table 5-41 and 43.

The variations of Ac are between 136.31 and – 20.89 where the minus value is ignored here as to indicating there are no useable space available for net courtyard area with building floor area exceeding the allocated net plot area. According to the plot dimension, a set of corresponding rectangular courtyard plan variations for three storey housing is shown in Figure 5-23. Ap remains the same as shown in one and two-storey housing. The increases of CAR that corresponds to 5 to 20m of the plot frontage in parametric variations are almost 50% compared to the base case. This in turn shows the effect of reducing the plot frontage on the variation of solar radiation tends to be two times as much as greater in higher-storey housings than in lower-storey housings.

Table 5-42. Plot depth for plot dimension and its corresponding courtyard dimension

Plot dimension	f = 5 m	f = 10 m	f = 15 m	f = 20 m	f = 25 m
Ap	228.75	215	201.25	187.5	173.75
Ac	136.31	97.01	57.71	18.41	-20.89
Sr	0.56	0.56	0.56	0.56	0.56
Sn	4.55	4.55	4.55	4.55	4.55
f	5	10	15	20	25
X_o	45.75	21.5	13.42	9.38	6.95
$d_{c.max}$	40.64	16.39	8.31	4.27	1.84
$f_{c.max}$	5	10	15	20	25

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Table 5-43. Effect of plot dimension on courtyard coverage and solar radiation for 3-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
f = 5 m	CAR	0.596			
	SOL	247.401	265.991	118.254	119.233
f = 10 m	CAR	0.451			
	SOL	157.817	173.107	89.721	94.015
f = 15 m	CAR	0.287			
	SOL	106.934	110.765	55.152	56.189
f = 20 m	CAR	0.098			
	SOL	42.998	54.356	18.094	24.374
f = 25 m	CAR	-			
	SOL	-	-	-	-

In summer, the ranges of 54.36 – 265.99 GJ in maximum solar radiation are recorded, deviating from changing f of two-storey case by –54.59 and –3.66 GJ. Minima of 43 – 247.4 GJ are shown deviating between –63.98 and +4.97 GJ from the two-storey housing to stand for sharp increases of solar radiation accompanied by CAR. An increase of 204.4 – 211.64 GJ is shown compared to the base case. In winter, the range of 24.34 – 119.23 GJ in maximum solar radiation indicate the deviations of –52.78 and 4.22 GJ to the two-storey case and the range of 18.094 – 118.25 GJ in minimum, deviating –2.75 and –58.44 GJ. Along with the variation in CAR, the range of the amount of solar radiation varies between 24.33 and 28.13 GJ for one-storey. However, for three-storey, the effect of reducing the plot frontage on the range of solar radiation results in a steep raise (94.89 – 100.16) from the base case. It seems that the amounts of solar radiation for the three-storey housing exceed those for lower-storey housings with narrowing the frontage of the house plot, implying that a relatively narrow plot frontage could be more beneficial in obtaining solar radiation in higher-storeys during winter. Aspect ratio on $f_{c.max}$: $d_{c.max}$ for the courtyard plan dimensions ranges 21.74:1 – 1:12.13 (Table 5-44).

Table 5-44. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	f = 5	f = 10	f =15	f = 20	f = 25
I	1:5.45	1.03:1	3.9:1	21.74:1	-
II	1:6.88	1:1.3	2.62:1	11.82:1	-
III	1:8.96	1:1.83	1.6:1	4.94:1	-
IV	1:12.13	1:2.77	1:1.2	1.01:1	-

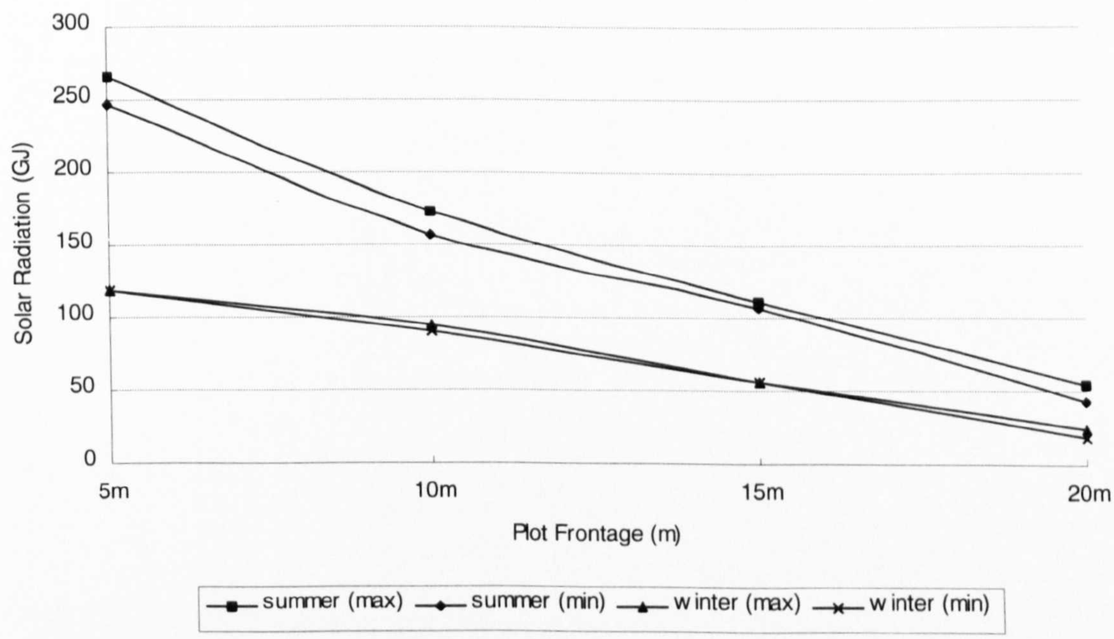


Figure 5-22. Solar radiation variations for three-storey housing in changing plot dimension factor in E-W street layout with plot frontage to the south direction

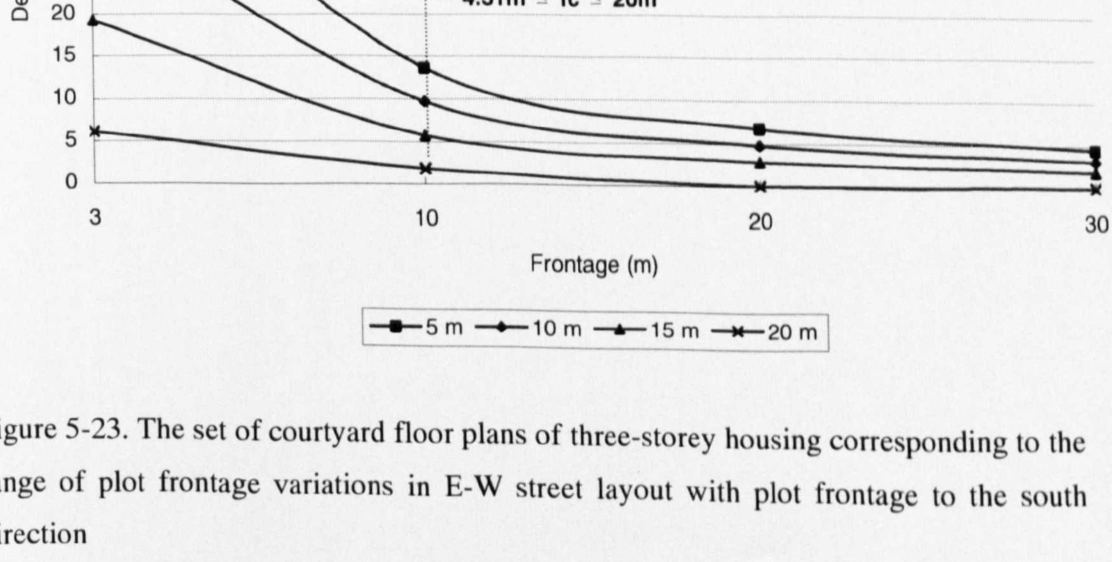


Figure 5-23. The set of courtyard floor plans of three-storey housing corresponding to the range of plot frontage variations in E-W street layout with plot frontage to the south direction

5-4-3. Housing Development Scale

The parametric analysis of the relationship of the housing development scale factor to CAR and solar radiation is performed and specified in Table 5-45 and 47.

Table 5-45. Variation in plot use in terms of housing development scale

Housing development scale	Ac	Ap	CAR (Ac / Ap)
50 units	56.21	199.75	0.281
100 units	56.21	199.75	0.281
500 units	57.71	201.25	0.287
1000 units	57.71	201.25	0.287
1500 units	57.21	200.75	0.285

Table 5-46. Plot depth for housing development scale and its corresponding courtyard dimension

Housing development scale	50 units	100 units	500 units	1000 units	1500 units
Ap	199.75	199.75	201.25	201.25	200.75
Ac	56.21	56.21	57.71	57.71	57.21
Sr	0.56	0.56	0.56	0.56	0.56
Sn	4.55	4.55	4.55	4.55	4.55
f	15	15	15	15	15
x_0	13.32	13.32	13.42	13.42	13.38
$d_{c.max}$	8.21	8.21	8.31	8.31	8.27
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_0 - (Sr + Sn)$
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Ac varies between 56.21 – 57.21m² while the ranges of Ap held constant as 199.75-200.75m². A set of rectangular courtyard plan variations according to housing development scale variations for three-storey housing is shown in Figure 5-25. Since the ranges of 0.281 – 0.285 are observed to result in 0.4% increase from the base case, the effects in relation to increasing building height are negligible as observed previously in the case for one and two-storey. Maxima of solar radiation in summer are formed as 108.69 – 110.95 GJ deviating –27.97 and –27.12 GJ from the two-storey case. Minima of 104.46 – 106.87 GJ with –17.34

and –16.31 GJ in deviation show a steady increase in the amounts of solar radiation along with increasing building height. An increase of 2.25 – 2.41 compared to the base case is indicated. In winter, the ranges of 54 – 56.63 GJ in maximum and 53.4 – 54.97 GJ in minimum solar radiation are generated resulting in the deviations ranging from –45.66 to –45.29 GJ for the maximum and –40.27 and –39.63 for the minimum respectively. Changes of 1.58 – 2.62 GJ compared to the base case are recorded (Figure 5-24). Again, as far as housing development scale factor is concerned, the effects of increasing number of housing units in a development on CAR and solar radiation for both summer and winter period are small by comparison to the other factors for any given storey of the housing. This is with the assumption that housing development is carried out in compliance with the building code. The courtyard plan dimensions relating to the ranges of the number of housing units based on the four dimension bands are 4:1 – 1:1.2 in the aspect ratio on $f_{c.max} : d_{c.max}$ (Table 5-48).

Table 5-47. Effect of housing development scale on courtyard coverage and solar radiation for 3-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
50 units	CAR	0.281			
	SOL	104.457	108.693	53.395	54.005
100 units	CAR	0.281			
	SOL	104.457	108.693	53.395	54.005
500 units	CAR	0.287			
	SOL	106.624	110.948	54.745	56.626
1000 units	CAR	0.287			
	SOL	106.624	110.948	54.745	56.626
1500 units	CAR	0.285			
	SOL	106.866	110.134	54.974	55.500

Table 5-48. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	50 units	100 units	500 units	1000 units	1500 units
I	4:1	4:1	3.9:1	3.9:1	3.94:1
II	2.68:1	2.68:1	2.62:1	2.62:1	2.65:1
III	1.63:1	1.63:1	1.6:1	1.6:1	1.62:1
IV	1:1.2	1:1.2	1:1.2	1:1.2	1:1.2

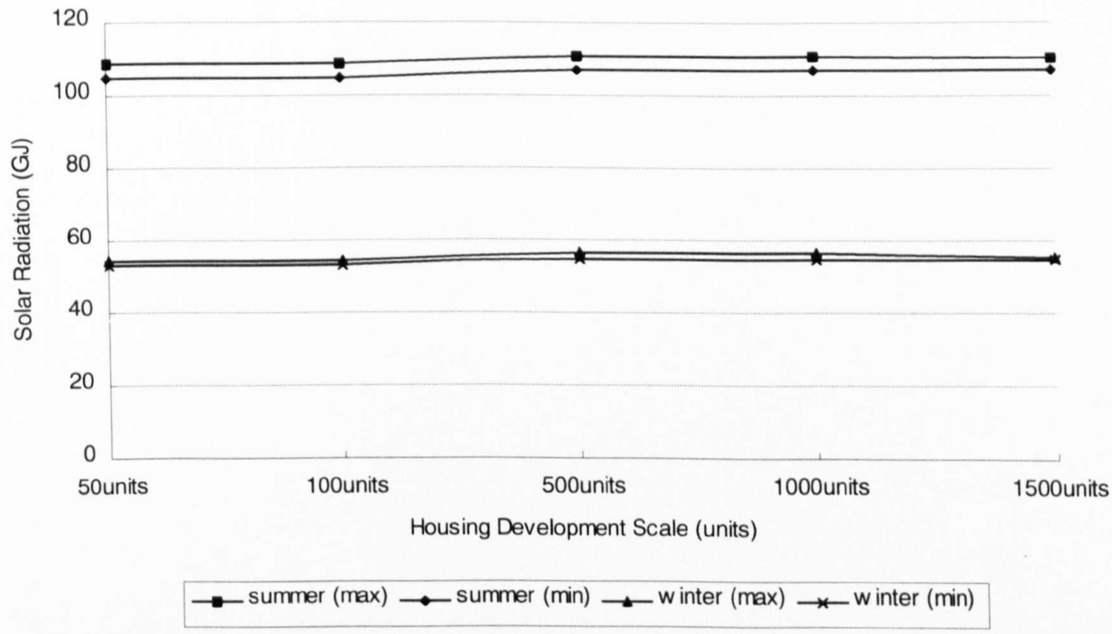


Figure 5-24. Solar radiation variations for three-storey housing in changing housing development scale factor in E-W street layout with plot frontage to the south direction

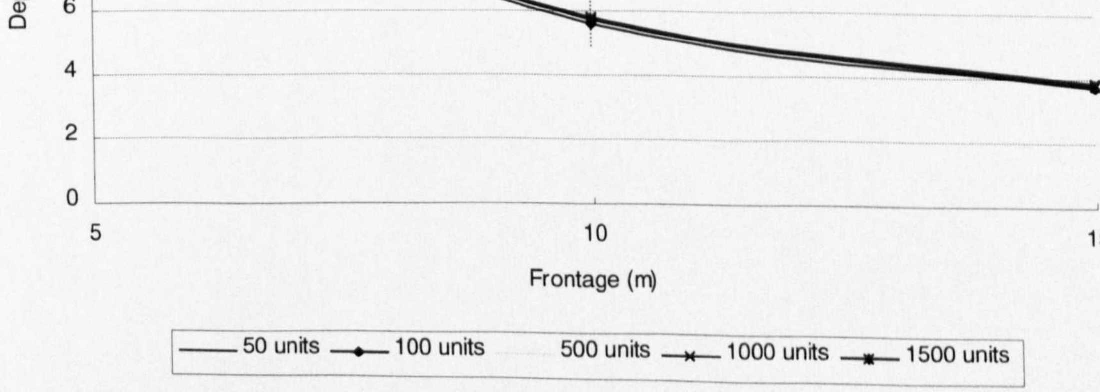


Figure 5-25. The set of courtyard floor plans of three-storey housing corresponding to the range of housing development scale variations in E-W street layout with plot frontage to the south direction

5-4-4. Housing Orientation (housing layout with parallel street E-W with frontage to the north)

In E-W layout with plot frontage to north, the relation of density factor to CAR and solar radiation for one-storey housing, in which housing densities are changed from 30 to 50 units/hectare, is investigated (Table 5-49, 50 and 51).

Table 5-49. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	209.13	284.42	0.735
35 units/hectare (t=0.974)	161.75	237.04	0.682
40 units/hectare (t=0.97)	125.96	201.25	0.626
45 units/hectare (t=0.966)	98.13	173.42	0.566
50 units/hectare (t=0.962)	75.86	151.15	0.502

Table 5-50. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	209.13	161.75	125.96	98.13	75.86
Sr	0.56	0.56	0.56	0.56	0.56
Sn	0	0	0	0	0
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	18.4	15.24	12.86	11	9.52
$f_{c.max}$	15	15	15	15	15

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - Sn$ ($Sn \geq Sr$) or $X_o - Sr$ ($Sn \leq Sr$)
Maximum dimension of courtyard in frontage: $f_{c.max} = f$

Ac ranges from 75.86 to 209.13, which corresponds to CAR range of 0.502 – 0.735. In Figure 5-27 is shown a set of rectangular courtyard floor plans according to the density variations for three storey housing. Accordingly CAR of 23% (0.233) whose variation indicates a slight increase compared to lower storeys is observed; that is that E-W layout with frontage to north seems to obtain larger net courtyard area than E-W layout to south throughout the given density range.

Table 5-51. The effect of housing density on courtyard coverage and solar radiation for 1-storey for housing layout running street N-S

		Summer		Winter	
		min	max	min	max
30	CAR	0.735			
units/ hectare	SOL	264.989	289.5	183.98	195
35	CAR	0.682			
units/ hectare	SOL	217.025	236.507	148.911	155.548
40	CAR	0.626			
units/hectare	SOL	181.054	196.471	121.08	121.704
45	CAR	0.566			
units/hectare	SOL	152.765	162.656	94.157	95.102
50	CAR	0.502			
units/hectare	SOL	130.315	132.669	73.543	73.711

Table 5-52. Ratio of shapes for courtyard dimensions corresponding to parametric variations (ratio of courtyard shapes = $f_{c.max} : d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1.08:1	1.39:1	1.79:1	2.29:1	2.96:1
II	1:1.1	1.13:1	1.4:1	1.71:1	2.11:1
III	1:1.32	1:1.11	1.06:1	1.22:1	1.4:1
IV	1:1.62	1:1.44	1:1.31	1:1.23	1:1.19

However there is only small increase in variation caused by density change. Figure 5-26 indicates that summer solar radiation ranges from 132.67 to 289.5 GJ in maximum, indicating the differences of 52 – 137.66 GJ compared to lower-storey cases. Minimum of solar radiation ranges from 130.31 to 264.99 GJ, which deviates from low-storey cases about 61.85 – 133.66 GJ. Hence the results indicate that the amounts of solar radiation received are higher at the density increase from 30 to 50 units/hectare than those of the other plot locations.

For the variations in solar radiation, there are increases of 156.83-134.67 GJ compared to the base case. In addition maximum range of 73.71 – 183.98 GJ in winter solar radiation show deviations of 11.59 and 183.98 compared to lower-storeys case and minimum range of 73.54 – 195 GJ deviating between –4.78 and 74.46. This indicates a change of the amounts of solar radiation tend to be remarkable in three-storey case compared to lower storey cases by showing an increase of 110.27 – 121.46 GJ from the base case. Therefore this implies that locating a plot in E-W layout with frontage to north is more advantageous than E-W layout to south especially in relatively high density bands where high winter solar radiation is required. Four types of the courtyard plan dimensions corresponding to each density bands vary from 2.96:1 to 1:1.62 in aspect ratio on $f_{c.max}$: $d_{c.max}$(Table 5-52).

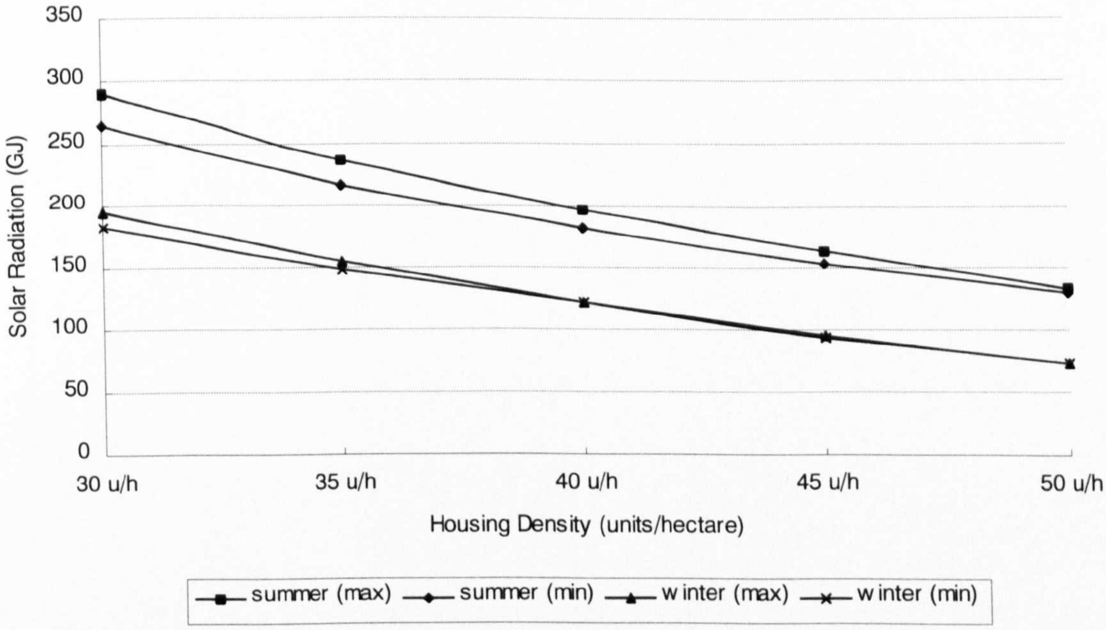


Figure 5-26. Solar radiation variations for three-storey housing in changing housing density factor in E-W street layout with plot frontage to the north direction

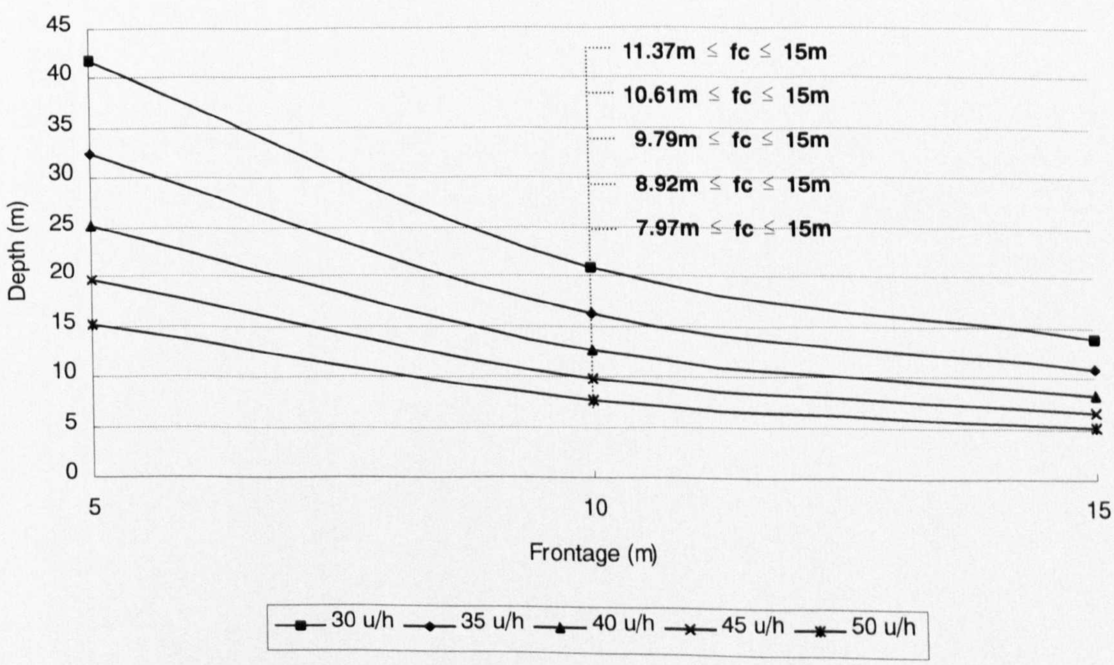


Figure 5-27. The set of courtyard floor plans of three-storey housing corresponding to the range of housing density variations in E-W street layout with plot frontage to the north direction

5-4-5. Housing Orientation (facing parallel street N-S)

A study of the effect of changing the housing density for three-storey courtyard housing of the N-S layout is carried out to develop the ranges of CAR (Table 5-53) and solar radiation (Table 5-55).

Table 5-53. Variation in plot use in terms of housing density

Density	Ac	Ap	CAR (Ac / Ap)
30 units/hectare (t=0.977)	125.41	284.42	0.441
35 units/hectare (t=0.974)	92.4	237.04	0.390
40 units/hectare (t=0.97)	67.45	201.25	0.335
45 units/hectare (t=0.966)	48.08	173.42	0.277
50 units/hectare (t=0.962)	32.54	151.15	0.215

Table 5-54. Plot depth for housing density and its corresponding courtyard dimension

Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Ap	284.42	237.04	201.25	173.42	151.15
Ac	125.41	92.4	67.45	48.08	32.54
Sr	0.56	0.56	0.56	0.56	0.56
Sn	4.55	4.55	4.55	4.55	4.55
f	15	15	15	15	15
x_o	18.96	15.8	13.42	11.56	10.08
$d_{c.max}$	18.4	15.24	12.86	11	9.52
$f_{c.max}$	10.45	10.45	10.45	10.45	10.45

Maximum dimension of courtyard in depth: $d_{c.max} = X_o - Sr$
Maximum dimension of courtyard in frontage: $f_{c.max} = f - Sn$

As a consequence, Ac ranges from 32.54 to 125.41m² in line with Ap of 151.15- 284.42m² by changing the housing density. Figure 5-29 indicates a set of rectangular courtyard plans corresponding to density variations for three-storey housing for N-S layout. The range of CAR is 0.215 – 0.441, tending to increase by mere 23% compared to the base case, which indicates there is no such a difference in the variations of CAR throughout any given housing storey. Furthermore, when increasing building height, it is also interesting to compare the plot orientation, indicating N-S layout seems to be more beneficial in ensuring larger net courtyard area than E-W layout with frontage especially to north by 4 – 17% in the density of 50 units/hectare.

Table 5-55. Effect of housing density on courtyard coverage and solar radiation for 3-storey for housing layout running street E-W

		Summer		Winter	
		min	max	min	max
30	CAR	0.441			
units/ hectare	SOL	179.402	186.219	120.477	121.408
35	CAR	0.390			
units/ hectare	SOL	147.194	153.542	88.801	89.473
40	CAR	0.335			
units/hectare	SOL	118.858	123.916	64.375	65.073
45	CAR	0.277			
units/hectare	SOL	94.445	95.582	45.596	47.113
50	CAR	0.215			
units/hectare	SOL	69.763	70.012	30.856	30.856

As indicated in Figure 5-28, the range of 70.01 – 186.22 GJ in the maximum solar radiation in summer is shown in the deviations of –38.19 and – 0.38 from results of the density changes of two-storey housing. The range of 69.76 – 179.4 GJ in minimum solar radiation corresponds to a range of the deviations between –22.11 and 10.33 GJ. In higher densities, the amounts of summer solar radiation of N-S layout reach higher than those of E-W layout to south, and lower than E-W layout to north. Besides, increases of 109.64 – 116.21 GJ in the variation are found from the base case, which is much smaller increase compared especially to those of E-W layout with frontage to south. In winter, the ranges in the maximum solar radiation are 30.86 – 121.41 GJ indicating deviations of –30.73 and –46.64 GJ; the ranges in the minimum are 30.86 – 120.48 GJ. Compared to the two-storey case in N-S layout with density changes, it deviates between –30.73 and –46.64 in the maximum and –27.61 and –32.34 GJ in the minimum ranges. Thus, the variations on average in solar radiation for N-S layout fluctuate in a quite narrower range with decreasing the housing density than those for E-W layout for both summer and winter period. This suggests that, under the assumption of changing the number of housing units per hectare, N-S layout is less sensitive than E-W layout. Accordingly, the amounts of winter solar radiation rise more significantly in the plot locations from E-W layout with frontage to north, to N-S layout, to E-W layout with frontage to south when increasing housing density. Referring to the general increases of 89.62 to 90.55 GJ to the base case, it is interesting that the amounts of solar radiation of N-S layout become close to those of E-W layout to north for higher storey especially at high density. Aspect ratio of 3.36:1 – 1:2.78 on $f_{c.max}$: $d_{c.max}$ is shown for the ranges of the courtyard plan dimensions by changing housing density in N-S layout (Table 5-56).

Table 5-56. Ratio of shapes for courtyard dimensions corresponding to parametric variations (aspect ratio of courtyard shapes = $f_{c.max}$: $d_{c.max}$)

Courtyard dimension	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
I	1:1.15	1.18:1	1.62:1	2.27:1	3.36:1
II	1:1.47	1:1.14	1.13:1	1.47:1	2.02:1
III	1:1.95	1:1.63	1:1.39	1:1.18	1.02:1
IV	1:2.7	1:2.51	1:2.45	1:2.52	1:2.78

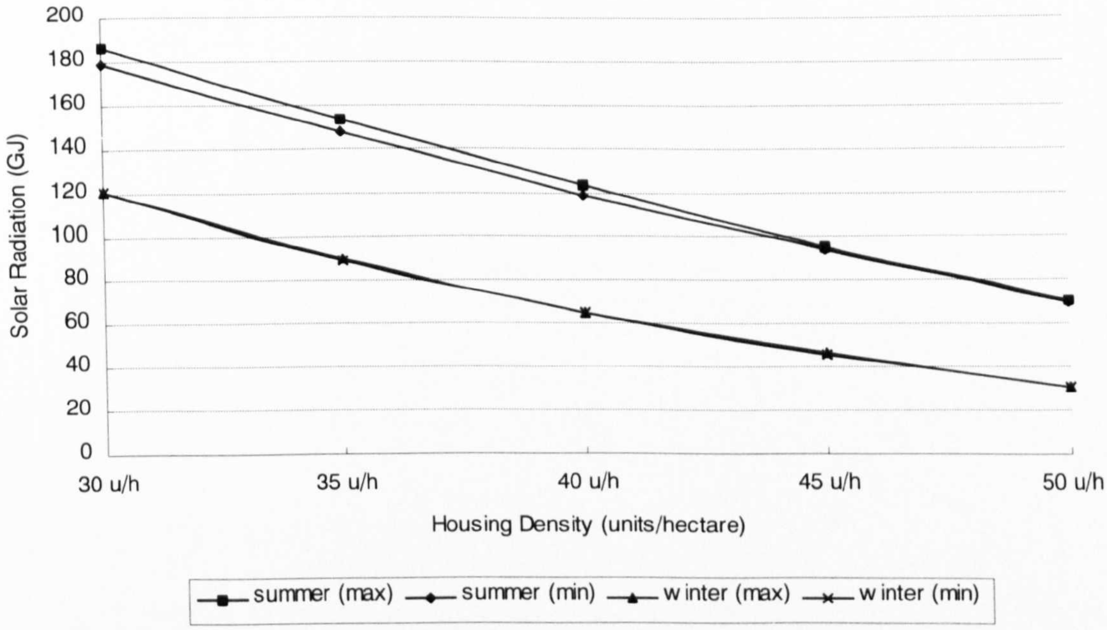


Figure 5-28. Solar radiation variations for three-storey housing in changing housing density factor in N-S street layout with plot frontage to both the east and the west

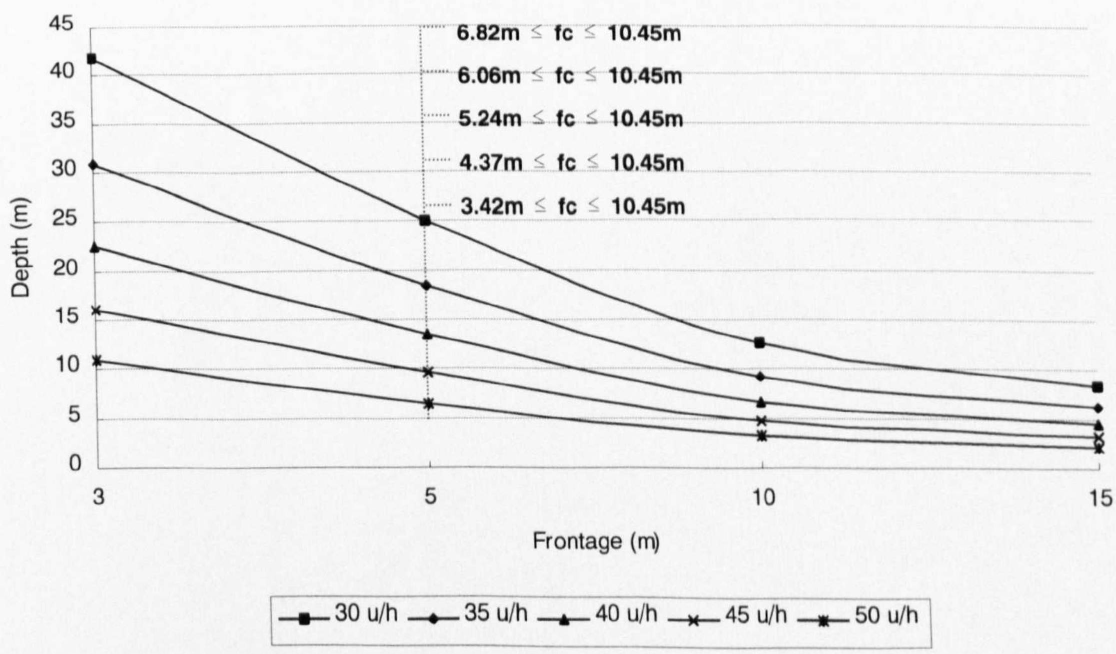


Figure 5-29. The set of courtyard floor plans of three-storey housing corresponding to the range of housing density variations in N-S street layout with plot frontage to both the east and the west direction

5-5. Summary of the results of model simulations

Based on all the above investigations on the relationship between the parametric variations of the housing layout factors and the amounts of solar radiation for the courtyard housing model, the main results are summarised as follows.

1. Modification of the density factor with layout of parallel streets E-W, as shown in Table 4-1, 21 and 41, the Courtyard Area Ratio (CAR) increases by 25% as housing density decreases from 50 units/hectare to 30 units/hectare for one-storey housing. However the change in CAR for multi-storey housing becomes more marked rising by approximately 45% for the three-storey case over the same ranges of the housing density. This CAR rise indicates that the gain in Courtyard Area Ratio caused by decreasing the housing density is enhanced as the numbers of storeys increases.

2. Examination of solar radiation in summer and winter based on changing housing density in E-W layout reveals that there is a tendency for relatively similar variations as for in CAR within the ranges of the housing density. For instance, in winter, the amounts of solar radiation increase by approximately 49 – 55 GJ when increasing the housing density for one-storey housing but there is more noticeable rise in solar radiation ranging from 122.7 –126 GJ for three-storey housing (Table 4-3, 43). Thus, the results can be interpreted that the average density effects on the amounts of solar radiation of all the generic courtyard types become greater as the number of building storeys increases. In addition, it is also interesting to see that the amounts of solar radiation recorded for the three storey housing exceeds those for one storey housing indicating the density effect becomes more marked in the taller building as the density becomes lower.

3. The major implication of changing the plot dimension factor in courtyard

housing plot with the layout of parallel street E-W is that CAR increases with reducing, f, the frontage of the plot (Table 4-5, 25, 45). With reducing the plot frontage from 25 to 5m, CAR becomes particularly marked in higher storey housing. For example, reducing f in one-storey housing leads to increases of 22% in CAR, three-storey housing with the ranges of f between 5-20m has increases of about 50% (Table 4-7, 27, 47).

4. The solar radiation variations in winter are also found to increase remarkably with changing f as the height of the housing increases. In winter, the variations in one-storey housing range from 24.3 to 28 GJ when there is a wider variation of 95-204 GJ in three-storey housing. Thus, this indicates that elongating housing plots by reducing f combined with increasing building height, whilst maintaining same net plot area, can be advantageous in increasing overall solar gain.

5. As far as the effects of the housing development scale factor on CAR and solar radiation is concerned, the variations in the number of housing units of an urban development with E-W street layouts have a relatively negligible effect. There are variations of 0.1 – 0.2% in CAR caused by changing from 50 to 1500 units in the housing development scale (Table 4-9, 29, 49).

6. Further investigations on the relationship between housing development scale factor and solar radiation indicate that the solar radiation variations of the courtyard housing for the ranges of building height are also relatively small compared with those in the other three factors, fluctuating between 0.53 – 0.64 GJ and 1.6 – 2.6 GJ for one and three storey housing respectively. Although the difference of t value, which is the proportion of net plot area to total plot area including the minimum community facility allocation under the building codes, partly affects the variations in solar radiation in both summer and winter by indicating some fluctuations, this is unlikely to be very significant (Table 4-11, 31, 51).

7. In E-W layout with frontage to north, the variations in CAR are about 22% for one and two-storey housing, and 23% for three-storey housing when changing housing density. This indicates that variability for CAR is small as a result of changing housing density especially in relatively high density bands (40 – 50 units/hectare) when particularly compared to the variations resulted from E-W layout with frontage to south.

8. The analysis on the relationship between E-W layout to north and solar radiation indicates that, in general, the amounts of solar radiation are higher throughout the whole density range than those of E-W layout to south. This is due to the alleviation of setback spacing to front road, based on the current building practice, caused by locating the road to north side of a plot in E-W layout. By that means, the difference of the amounts of solar radiation between E-W layout with frontage to south and to north becomes more important with increased housing storeys, indicating E-W layout to north might be utilised in situations requiring maximised plot-use.

9. The study of the effect of variations in the housing density factor on the layout of N-S street indicates that the variations in CAR are found to be relatively small. In fact, the overall effect on the relation between the housing density and CAR of the N-S layout results in smaller CAR swings than those of the E-W layout, showing 21% (one-storey) and 23% (three-storey) increases in CAR variations. However it is worth noting that the higher the housing density and the number of building storeys, the higher CAR becomes compared to those of the E-W layout with frontage to south. For instance, there are differences of 4 – 17% on average of CAR between the housing layout of E-W to south and N-S for a parametric variation of 50 units/hectare. Compared to E-W layout with frontage to north, in general, N-S layout has slightly lower levels of CAR as housing storey increases. However, in looking at the differences of CAR in variations to the density change, there are no significant differences between N-S layout and E-W layout to north.

10. In terms of plot orientation factor (Table 4-19, 39, 59), it is interesting to discover that by increasing the height of the courtyard housing the greater winter solar gain occurs in N-S layout with frontage to both east and west (50 units/hectare; three-storey; 20.6-20.7 GJ) along with E-W layout with frontage to north than E-W layout to south. Comparing N-S layout to E-W layout to north, plots in N-S layout have generally lower levels of sunlight in winter. However it is noticeable that the differences of the sunlight level between two plot locations become much smaller for higher storey especially at high density (3 storey; differences of 75 GJ in maximum and 64 GJ in minimum in 30 units/hectare and 43 GJ on average in 50 units/hectare). Therefore, this implies that, on average, N-S layout has generally even performance with relatively higher heat gain in winter in any given location of the layout. Although the winter solar benefits of the N-S layout are somewhat offset by additional cooling requirements due to higher solar gain in summer, the layout can be advantageous in obtaining the optimum winter solar radiation benefits in courtyards, particularly in the ranges of relatively high density bands.

Summary of the Chapter

After developing a series of simple theoretical model of courtyard housing layout in the previous chapter, this chapter is seen as pilot study, which mainly give attention to the general trends of CAR and solar radiation of the urban courtyard housing model by varying the housing layout factors. The results are produced based on using a series of the density expressions and the Shadowpack package 2.0, the computer tool described in the previous chapter. The results indicate that there are significant differences in the amount of CAR and corresponding solar radiation among the housing layout factors, which implies the needs of introducing a range of design strategies available for the future development. The results are given based on three steps.

Using Ap (net plot area) and Ac (net courtyard area) from the density expressions, a range of values for BC (building coverage) and CAR (courtyard area ratio) is calculated. Based on a given range of $f_{c.max}$ (courtyard frontage) and $d_{c.max}$ (courtyard depth) as well as Ap and Ac allocated by the variations in each housing layout factor, a range of courtyard plan is shown. The effect of variation in the solar performance of the internal courtyard facades is analysed.

After the first stage analyses based on parametric variations, it is possible to arrive at the results that;

① Courtyard Area Ratio (CAR), on the whole, shows a steady reduction when increasing the number of housing storeys with a view to utilising given plots at its maximum under the current building practice.

② In addition, further analyses indicate that increasing building height from one to two-storey contribute effectually toward obtaining higher amount of solar radiation.

However, by increasing the height to three-storeys where greater setback spacing is needed due to the building code, decreases of the amount of solar radiation become prominent compared to lower storey housings. Consequently, these contradict the general notion by implying that increasing the height of the housing in an urban environment would be feasible without losing benefits of solar radiation in the courtyard if the application of the building code for setback spacing became alleviated to high-storey building. Therefore, in order to further investigate the implications of solar radiation and building height for passive solar courtyard housing in urban area, the results and the analyses will be evaluated and re-interpreted in Chapter 6.

Chapter 6.

Evaluation and Interpretation of the Analyses

6-1. Interpretation of Results: Solar radiation variation with building height

The analyses have been carried out to investigate the relationship between CAR and solar radiation during summer and winter caused by variations in building height, based on the land-use and solar data given by a series of density expressions (Figure 6-1~15). Firstly, to give an extended interpretation of the results on a height basis, the ranges of the height are sub-divided as they consist of two bands of which the first consists of one and two storey housing (relatively small setback spacing) and the second of three-storey housing (relatively big setback spacing). This arises from differences in Korean land use accounting.

The analyses for the interpretation of the results are divided mainly into two stages.

1. A range of CAR and its corresponding solar radiation based on building height variation is evaluated.
2. To put the analyses to be summarised together, various modes of solar radiation strategies are studied in order to produce design combination by considering the relationship between the housing layout factors and solar radiation.

An attempt is made to provide recommendations of a range of operation for use by planners and designers. They may then use careful consideration of the factors to optimise solar radiation, whilst maintaining certain density standards.

For the purpose of the analyses, assessment criteria based on seasonal variations are used in which the effects of the housing layout factors on solar radiation with changing height are considered. The list of the main criteria is as follows;

Identification of,

1. The ranges of building height which affect most significantly the amounts of CAR and solar radiation on a seasonal basis.
2. The general ways of utilising the housing layout factors which affect the values of CAR and solar radiation.
3. The selection of the most important factors which seem to control CAR and solar radiation.
4. The advantages and the disadvantages of orientation of the housing plot in relation to the front road by comparing the values and the ranges of CAR and solar radiation recorded in each plot location.
5. The more effective ways of obtaining adequate CAR and solar radiation particularly in terms of orientating the housing plot in an urban environment where there tends to be an increase in the density of buildings.

6-1-1. Standard Variations in Courtyard Area Ratio (CAR)

In general, the values of CAR, which affect the useablility of courtyard space in the housing layout model, decrease whatever housing layout factors are used as the number of building storeys increases. Figure 6-1, 2, 3, 4 and 5 shows the fall in CAR associated with variations of the housing layout factors as the number of housing storeys increases. This is because the influences of setback spacing become greater due to the regulation code.

Importantly however, a marked increase in CAR can be found with two and three storey housing by decreasing D, the housing density, and/or reducing f, the plot frontage, in the E-W housing layout (Figure 6-1). In the analysis, for example, the maximum gain of 45% in CAR can be achieved by changing the housing density from 50 units/hectare to 30 units/hectare and 50% by changing the plot frontage from 20m to 5m for three-storey housing. This, in turn, confirms that the values of CAR change more sensitively in taller courtyard housing in response to variations in the housing layout factors. Thus an increase in housing density might in part be offset by reducing plot frontage.

For the housing layout of N-S street under the assumptions (f=15m, housing units=500units) used in the layout of E-W street, there are significant differences found between the two layouts in terms of the variations in CAR. For example, with housings on the E-W layout with frontage to south, the relation between the density factor and CAR becomes more sensitive as the building height was raised (one-storey; 25%, three-storey; 45%). However with housings on the N-S layout, the analyses indicate that changing building height does not change CAR as much compared to E-W layout in relation to the density factor (one-storey; 21%, three-storey; 23%). From the viewpoints of obtaining higher CAR, there is much smaller CAR swings in the N-S layout, showing less effect from the density factor and resulting in similar variations regardless of increasing building height.

Figure 6-3 shows that by increasing the number of housing units, the average effects in relation to the housing development factor are rather small compared with those effects of the other factors by varying from 0.2 to 0.4% at any building height.

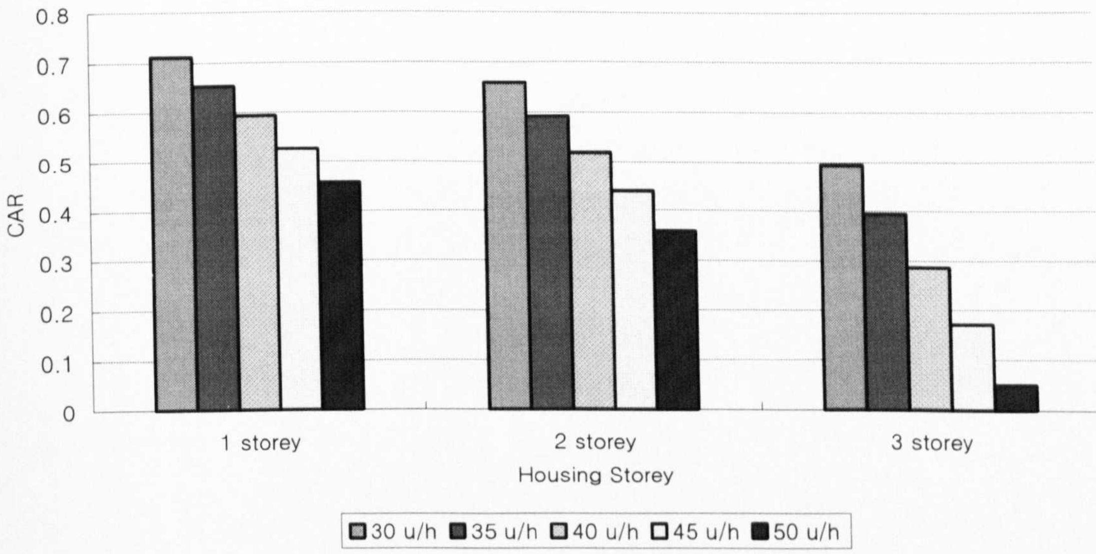


Figure 6-1. CAR variations for housings of different densities based on changing housing storey in E-W layout with frontage to the south

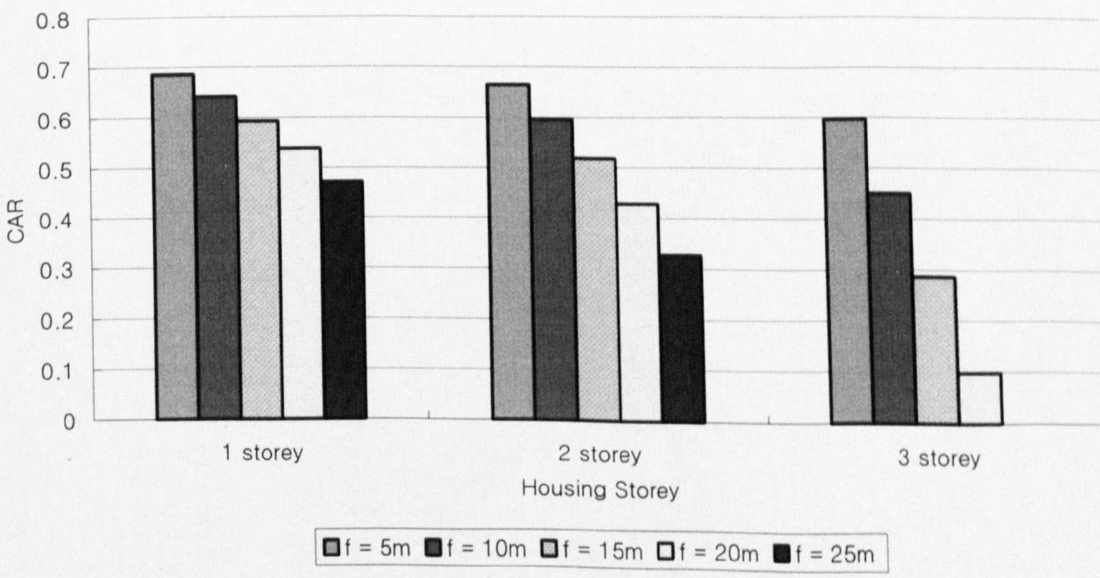


Figure 6-2. CAR variations for housings of different plot dimensions based on changing housing storey in E-W layout with frontage to the south

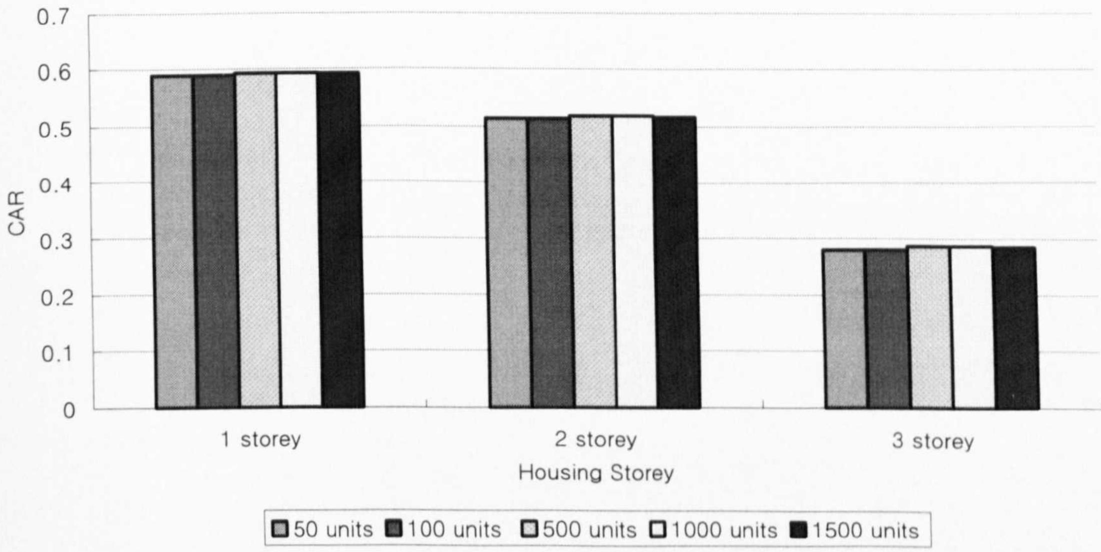


Figure 6-3. CAR variations for housings of different housing development scales based on changing housing storey in E-W layout with frontage to the south

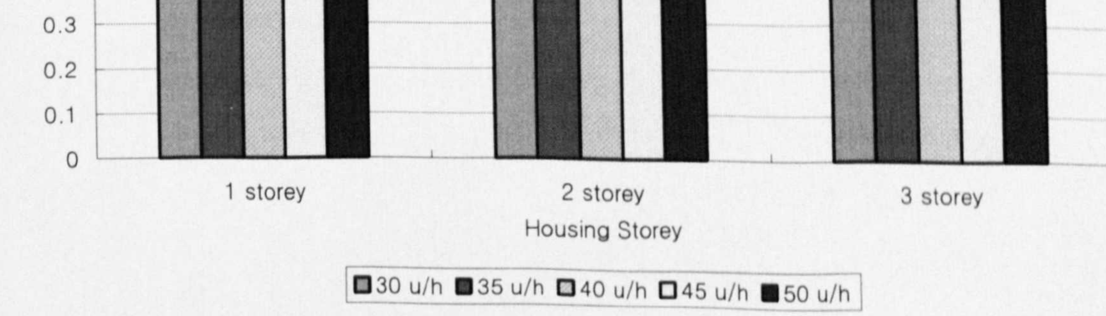


Figure 6-4. CAR variations for housings of different densities based on changing housing storey in E-W layout with frontage to the north

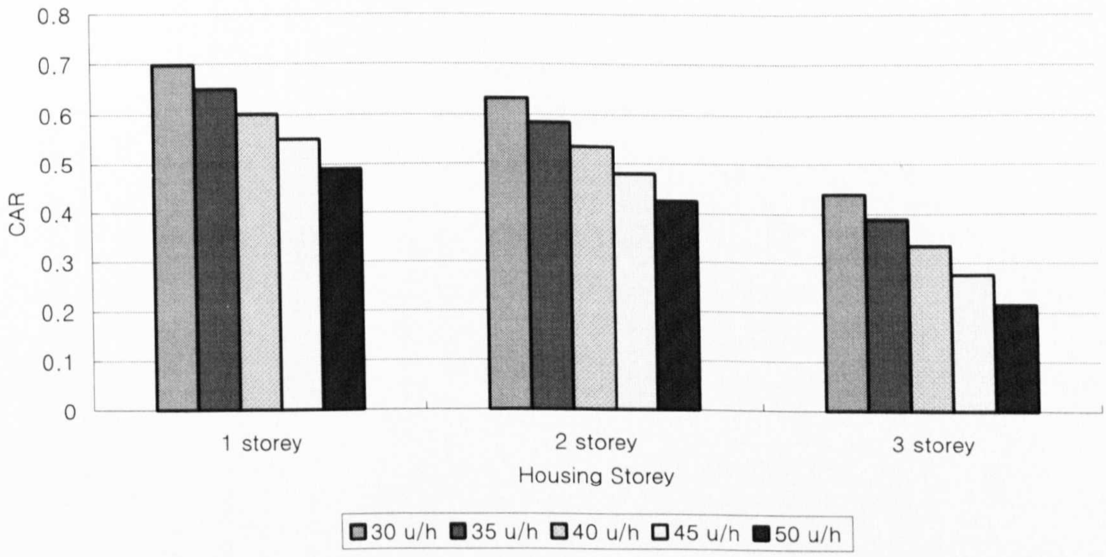


Figure 6-5. CAR variations for housings of different densities based on changing housing storey in N-S layout with frontage both to east and west

6-1-2. Building Height and Solar Radiation in Summer

A number of areas of interest can be investigated for summer solar radiation recorded in the courtyard-housing model based on building height variations.

First, the summer solar radiation has been tested against the different generic types of courtyards produced by variations of the housing layout factors such as the housing density, the plot dimension and the housing development scale, both on the E-W layout and the housing density on the N-S layout. The analyses indicate that, with increasing the number of storeys, the amounts of solar radiation tend to reduce or hold constant in between 2 - 3 storey after a steady increase at lower storey. (Figure 6-6,7,8,10). However, for E-W layout with frontage to north (Figure 6-9), the amounts of solar radiation start to increase from 2 storey, which is due to the least setback spacing application among the three plot location. This contrasts with the results in the variations in CAR where the amounts of CAR decrease in proportion to increasing the building height. Consequently, in general, this fall in solar gain becomes greater when increasing the height to 3 storeys and above in which more setback spacing is required due to the building code. In relation to this, Mohsen (1978) points out in the relationship of height in courtyard buildings and solar radiation that the deepness of the courtyard form significantly affects the irradiation load: in general, as the form gets increased in height, solar radiation increases up to a certain level of building height. Then, the amounts of solar radiation start to stagnate or decrease due to the shadow effect caused by walls. Therefore, in turn, the summer solar radiation of the courtyard has the limitation that the gain is limited once the building height reaches a certain point. For example, Figure 6-6 and 10 indicates both the E-W and the N-S layouts have the values of around 190-200 GJ in solar radiation with housing density of 30 units/hectare of the both layouts. But, raising the height from two to three-storey housing results in decreasing the amounts of solar radiation merely by –10 and –20GJ whilst solar radiation increases by 50 – 80GJ from one to two-storey housing.

Second, in terms of the relationship between summer courtyard solar radiation and the parametric variations of the housing layout factors, the ranges of three-storey housing show the greatest variations in solar radiation fluctuations whichever factors are changed. This, for instance, is shown in Figure 6-6 and 7 in the parametric variations of the housing density and the plot dimension factor, by indicating that the sensitivity of summer solar radiation to the variations of the factors becomes the greatest in three-storey housing – the highest range in height for the study. In addition, with regard to the corresponding Building Coverage (BC) in conjunction with the parametric variations of the two factors as above, the ranges of the building coverage are found well below the standards of the building code in which the minimum limitations on the BC should be no more than 50/100 in case of the residential area I (Table 3-5). This excludes the green belt area limit of 20/100, which is exceptionally low as it is provided mainly for suburban and rural areas. It is also found that the corresponding Floor Area Ratio (FAR) to the ranges of the Building Coverage exceeds 100% around the three-storey, which is more than the limitation for the plot utilisation for residential areas on average in terms of introducing the setback spacing (Appendix 1). This, for example, can be confirmed by observing a value of 133% in FAR in the housing density of 50 units/hectare on the E-W layout for three-storey housing. As a result, the overall analyses imply that it is not possible to plan more than two-storey housing in an urban environment where these types of residential area can commonly be found. Thus, after the analyses, referring to the trends on the increases of the sensitivity between the factors and solar radiation by raising the building height, it is recommended that a local authority should re-examine the implications of current land-use data on plot-use. There seems to be a good opportunity for further work to investigate utilisation of plot-use in relation to reducing the constraints on BC and FAR and shortening setback spacing, provided that courtyard spaces are planned to otherwise monotonous conventional plan housings in urban development.

Third, as in the case in CAR, the effect of variations in the housing development scale on summer solar radiation swing is between only 1 and 5GJ regardless of changing the building height, which is a relatively narrow range in comparison with the variations of the other factor (Figure 6-8).

Fourth, by comparing the maximum and the minimum values of summer solar radiation between the E-W layout (with frontage to south) and the N-S layout, analysis can be carried out based on the density ranges. In this, the analyses show that the value of solar radiation of the N-S layout gradually increases towards those of the E-W layout in high storeys (2-3 storey) situations on a low-density band (30units/hectare; E-W: 195-217GJ, N-S: 180-185GJ). In addition, in a high-density band, the N-S layout solar radiation exceeds those of the E-W layout (50units/hectare; E-W: 25GJ, N-S: 70GJ). In general, the analyses confirm that increase in the values of the summer solar radiation in the

N-S layout compared to those of the E-W layout become more evident in the high-density band of two to three storey housing.

Fifth, the amounts of solar radiation of E-W layout (with frontage to north) reaches higher than those of N-S layout at both low (3 storey; 30units/hectare: E-W: 265-290GJ, N-S: 180-185GJ) and high-density bands (3 storey; 50units/hectare: E-W: 130-133GJ, N-S: 70GJ). Therefore, in general, the amounts of solar radiation admitted to courtyards falls more significantly with plot orientations from E-W layout (frontage to north) to N-S layout to E-W layout (frontage to south) for high-density development.

Sixth, with regard to the relationship between the housing density factor and the solar radiation control on the plot locations, it appears that the effects of changing housing densities on the summer courtyard solar radiation become greater in the E-W layout than those in the N-S layout. For two-storey housing, in particular, the variations in solar radiation in the E-W layout (to south) and E-W layout (to north) are about 54 – 84GJ and 50 – 70GJ respectively by decreasing the housing density from 50 to 30 units/hectare whilst there are a 23 -56GJ increase in N-S layout respectively. This trend of the variations becomes more profound for three-storey housing; the variations in solar radiation in the N-S layout is half those in the E-W layout. In other words, in view of sensitivity between solar radiation and the housing layout factor, the variations in solar radiation of N-S layout is much less sensitive to the housing density changes than E-W layout.

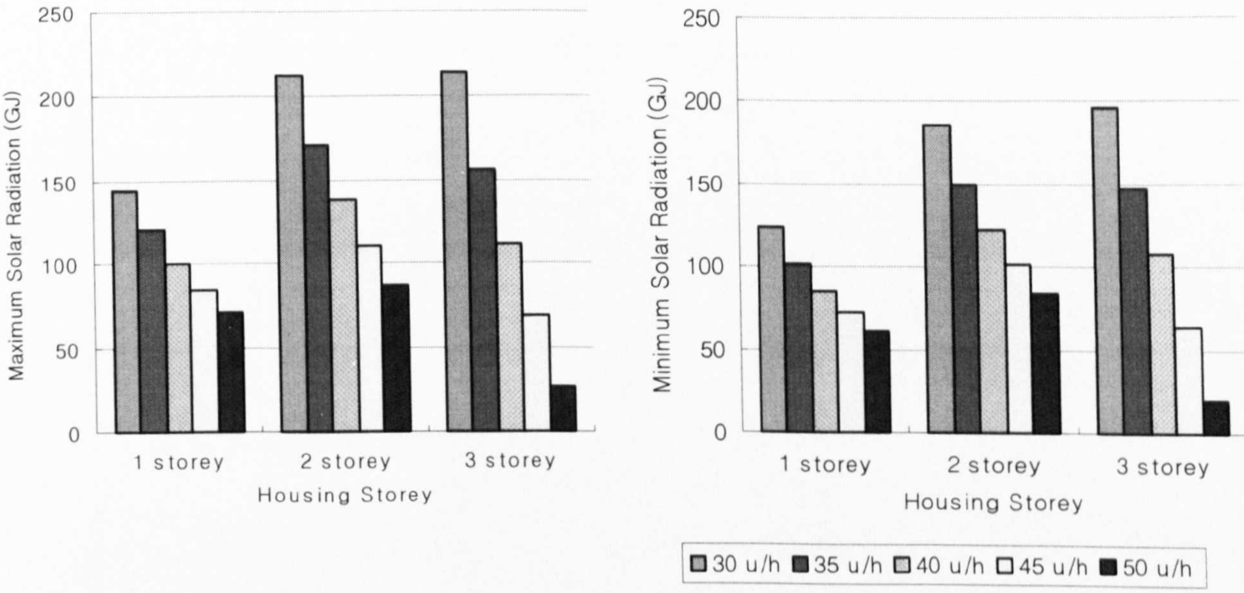


Figure 6-6. Summer solar radiation variations for housings of different densities based on changing housing storey in E-W layout with frontage to the south

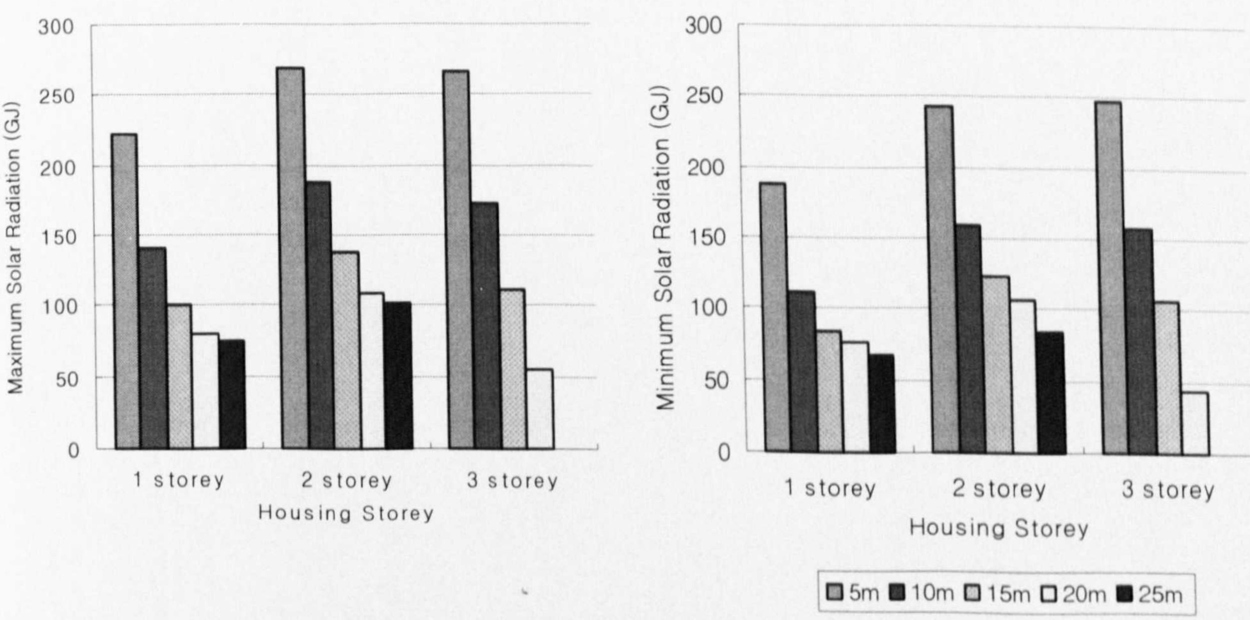


Figure 6-7. Summer solar radiation variations for housings of different plot dimensions based on changing housing storey in E-W layout with frontage to the south

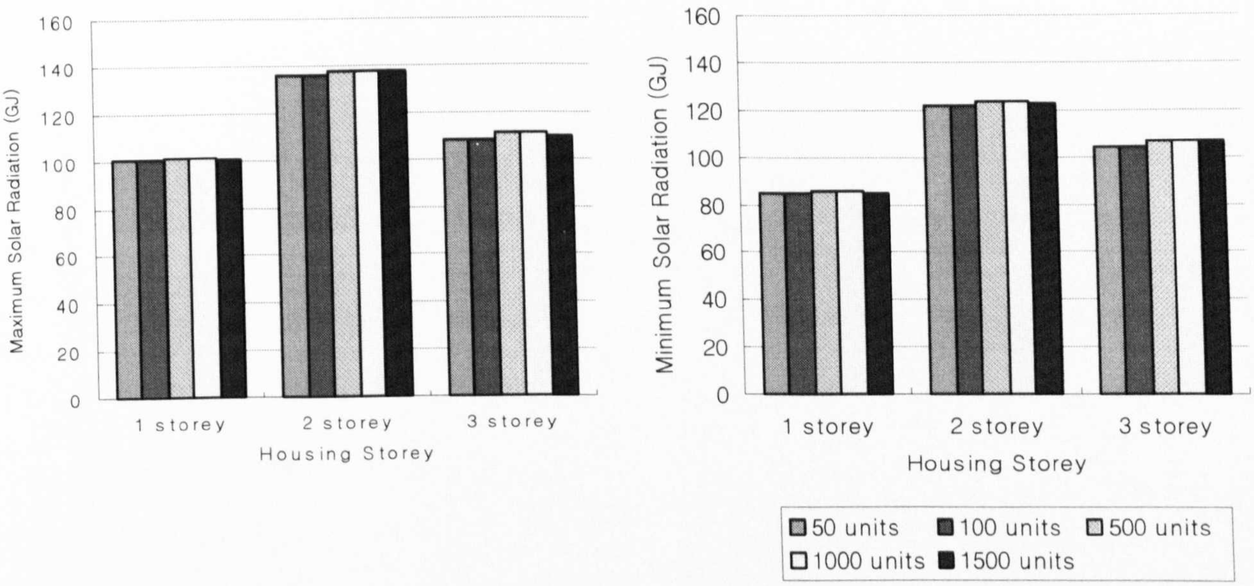


Figure 6-8. Summer solar radiation variations for housings of different housing development scales based on changing housing storey in E-W layout with frontage to the south

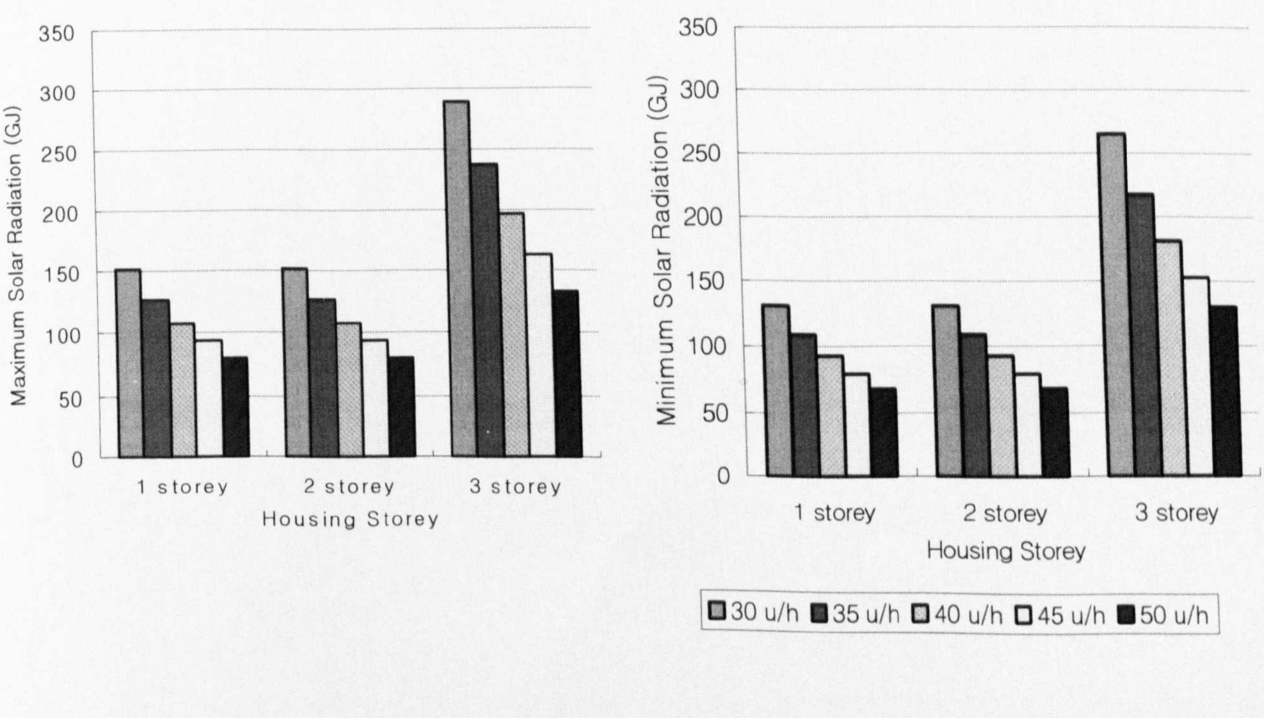


Figure 6-9. Summer solar radiation variations for housings of different densities based on changing housing storey in E-W layout with frontage to the north

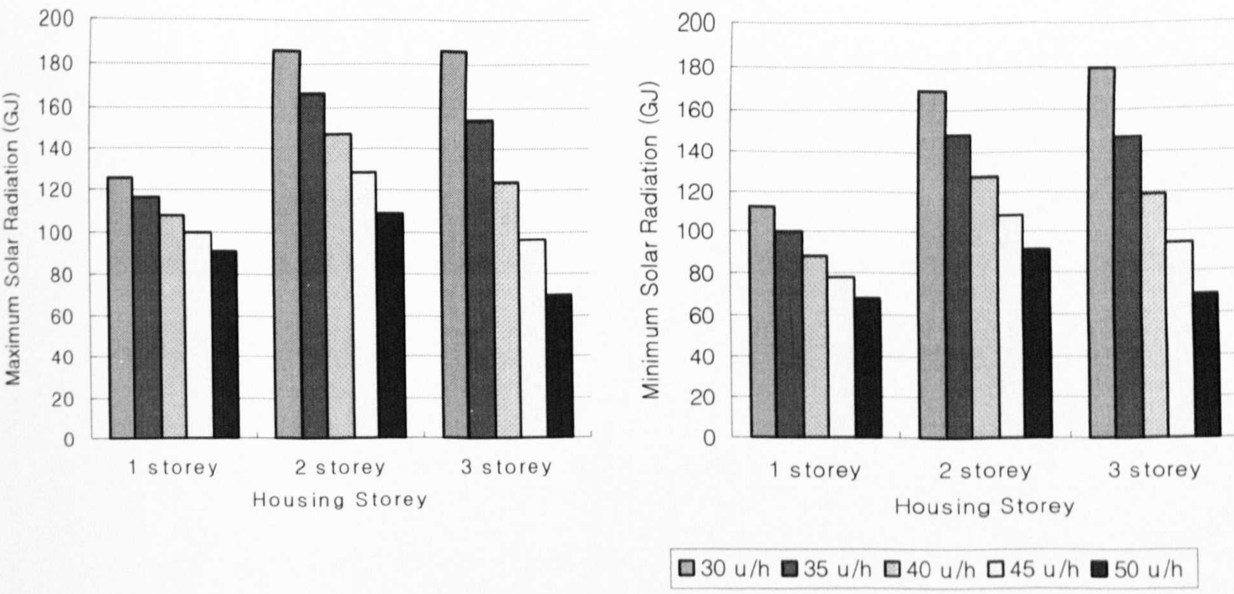


Figure 6-10. Summer solar radiation variations for housings of different densities based on changing housing storey in N-S layout with frontage both to east and west

6-1-3. Building Height and Solar Radiation in Winter

Again, several areas of interest can be identified in terms of winter solar radiation recorded in courtyard housing models based on building height variations.

First, the analyses of the overall pattern of the solar radiation variations indicate that the amounts of winter solar radiation tend to decrease more rapidly than those of summer solar radiation especially when raising building height from two to three-storey housing whilst maintaining the same size of ground housing area. This is due to the relatively low sun angle in winter period, which is most affected by overshadowing when solar gain is most desirable (Lewis et al, 1996). However it should be noted that the gain in the amounts of solar radiation received in the courtyard remains increases or stagnant when decreasing housing density between the range of one and two storey housing, and reducing plot frontage throughout the given ranges of housing storeys. The remarkable reductions in solar gain start to occur particularly in three-storey housing where bigger setback spacing is allocated from current building code. For example, Figure 6-11 indicates there are increases in the variations of 35-40GJ in solar radiation by raising from one to two-storey housing, and decreases in the variations of 8 – 22GJ from two to three-storey housing with density of 30 units/hectare on the E-W layout. In the 50 units/hectare density range, the winter solar radiation drops by 1.5 GJ in changing from one to two-storey and 42GJ from two to three-storeys which, in turn, shows a general trend of reducing the amounts of solar radiation as the height increases and the density increases. As the setback spacing guidelines are introduced to safeguard solar access between a row of housing for detached housing model, there arises a need to differentiate the level of the building code application to housing models. Furthermore, the differences in the variations from one to three-storeys tend to markedly reduce with reductions in the plot frontage caused by changing the plot dimension factors (f=5; 10 – 20GJ). This evidence further suggests that increasing the building height does not necessarily much affect variations of winter solar radiation when the plot frontage becomes narrower.

Second, the analyses, on the whole, indicate that, as the housing density (D) decreases and the plot frontage (f) reduces, the amounts of the winter solar radiation received in the courtyard increase (Table 6-11, 12). For instance, in the E-W layout (with frontage to south), the value of the winter solar radiation is 95-110GJ for two-storey and 125-130GJ for three-storey with a reduction of housing density (50units/hectare → 30units/hectare). With the reduction of the plot frontage (20m → 5m) in the E-W layout, the maximum value of 95-100GJ occurs. Under the same condition, in the E-W layout with frontage to north, the value is 45–55GJ for two-storey and 105-120GJ for three-storey housing. In the N-S layout, the average solar gain caused by changing the density factor is 100-115GJ for two-storey and about 90GJ for three-storey housing. In addition, the courtyard housing in the N-S layout tends to have greater sensitivity to changing the housing density factor in one two-storey range and lesser sensitivity in two to three-storey range than the E-W layout does.

Third, based on the analyses, general comparisons can be made between the housing density factor and the plot dimension factor. Decreasing plot frontage seems to be more beneficial in ensuring adequate solar gain than increasing the size of housing plot. For instance, there are increases of 33.8 – 34.8GJ in solar gain by changing housing density from 40 to 35 units/hectare, increasing 36.79 m^2 in net plot area (Ap) for three-storey housing. However, for the same building height, decreasing plot frontage from 15 to 5 m results in a net plot area increase to 27.50 m^2, which causes an increase of about 63-63.1GJ.

Fourth, it is also interesting to compare the E-W and the N-S layout in the light of achieving a certain density objective in terms of site planning whilst maintaining optimum solar gain into the courtyard. As shown in Figure 6-15, increasing the housing density causes smaller winter solar radiation swings in the three-storey range on the N-S layout than on the E-W layout with frontage to south. For example, as the density increases from 30 to 50 units/hectare on the E-W layout, a decrease of 126 – 128GJ in the solar radiation variations occurs. However, in the N-S layout, a reduction of 88 – 90GJ in the variations occurs, which is about two-thirds those of the E-W layout. Conversely, it implies that there does seem to be more efficient land-use benefit in adopting courtyard design on the N-S layout than the E-W layout in an urban environment where demands for higher density should be met. The analyses confirm that increasing the density does not lead to a relatively marked decrease in the winter solar gain in the N-S layout by comparison with the E-W layout (especially for two and three storey housings). Besides, the amounts of solar radiation of N-S layout reaches higher than those of E-W layout especially at high-densities ranging from 40 to 50uits/hectare as the number of storeys increases (3 storey; 50units/hectare; E-W: 10.2GJ, N-S: 30.9GJ). In terms of the urban housing density standards, it is generally suggested that the density of this type of housing, depending on size of units and site development, can be described as medium-density and generally will be similar to town house or terrace/row house densities (BRE, 1992). An approximate range would be from 12 units/acre (30 units/hectare) for large houses to 18 units (45 units) for small ones. In this respect, this provides a clue to achieve a certain range of density even higher than the standards without compromising the winter solar gain. This can be done by combining plot location and plot frontage using a layout with parallel streets running N-S with narrow frontage.

Fifth, Figure 6-13 indicates that, on the whole, it can be said that by increasing the number of housing units, the average effects for the heating period in relation to the housing development scale factor are negligible. This is with the assumption that housing development is carried out in compliance with the building regulation code.

Sixth, based on all the above the analyses, general observations can be made on selected design strategies for courtyard houses. In order to maximise the winter solar gain of courtyards in an urban environment, it must be stressed that housing models must take into account housing layout factors by means of positioning housing on a layout with streets running N-S with narrowing plot frontages, and optimising housing densities. In other words, only through the selection and adaptation of the housing layout factors such as plot location and plot frontage, can the urban courtyard housing design be justified, in which the higher solar gain normally only attainable in lower densities can be obtained and higher density thus achieved.

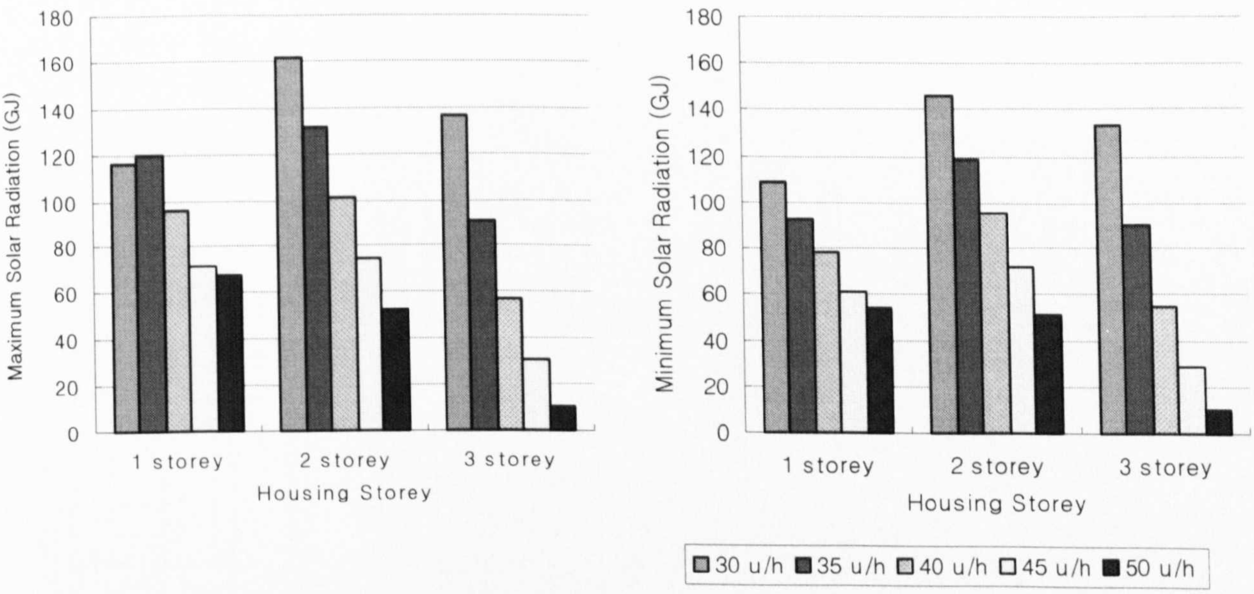


Figure 6-11. Winter solar radiation variations for housings of different densities based on changing housing storey in E-W layout with frontage to the south

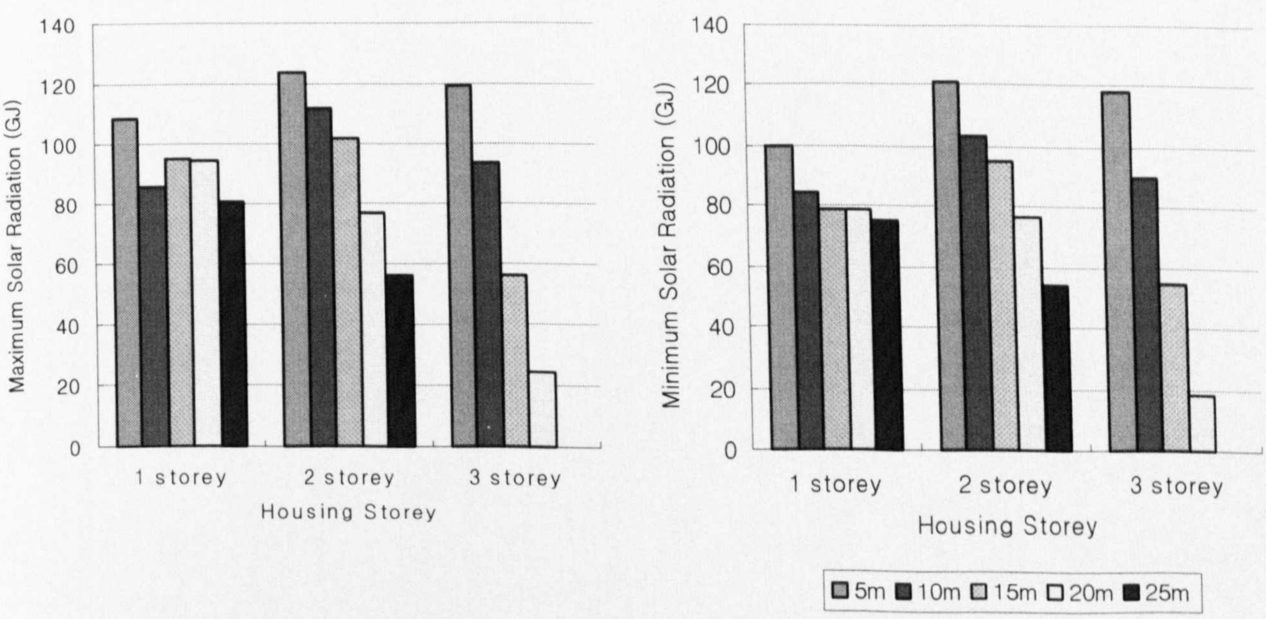


Figure 6-12. Winter solar radiation variations for housings of different plot dimensions based on changing housing storey in E-W layout with frontage to the south

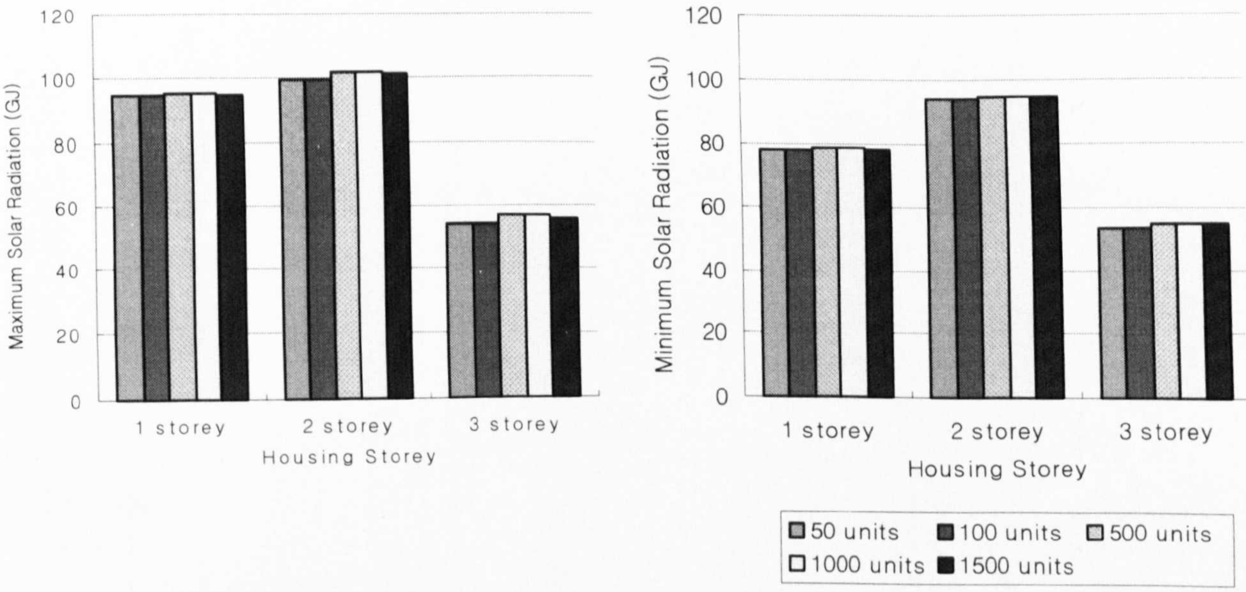


Figure 6-13. Winter solar radiation variations for housings of different housing development scales based on changing housing storey in E-W layout with frontage to the south

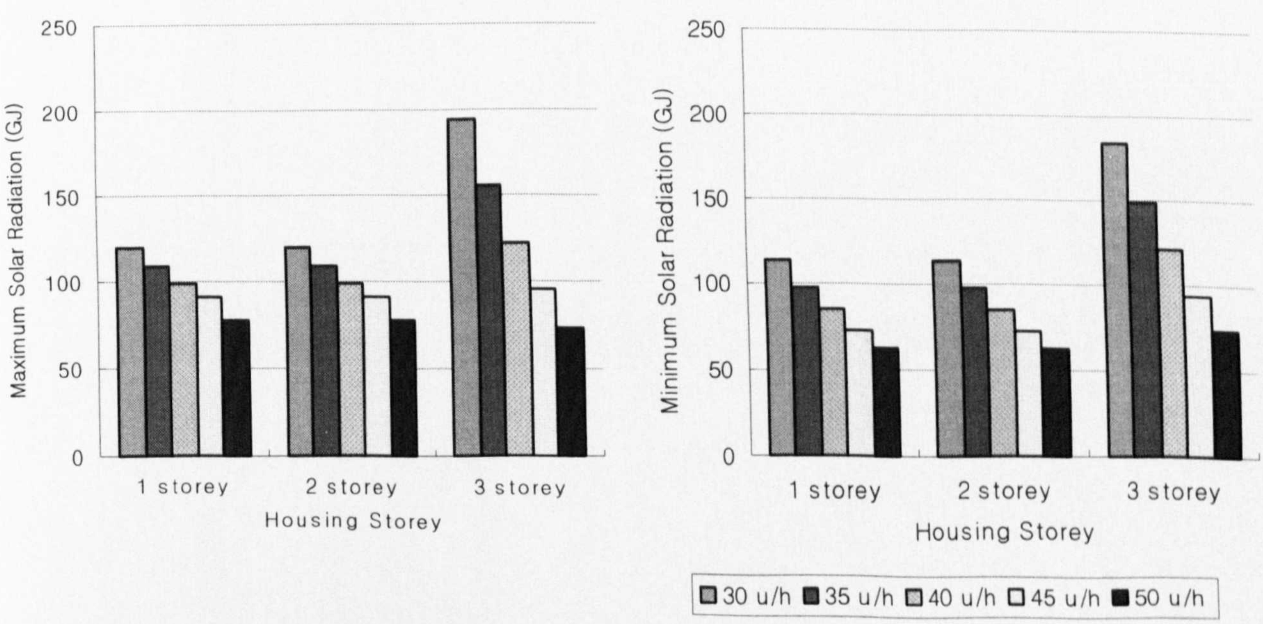


Figure 6-14. Winter solar radiation variations for housings of different densities based on changing housing storey in E-W layout with frontage to the north

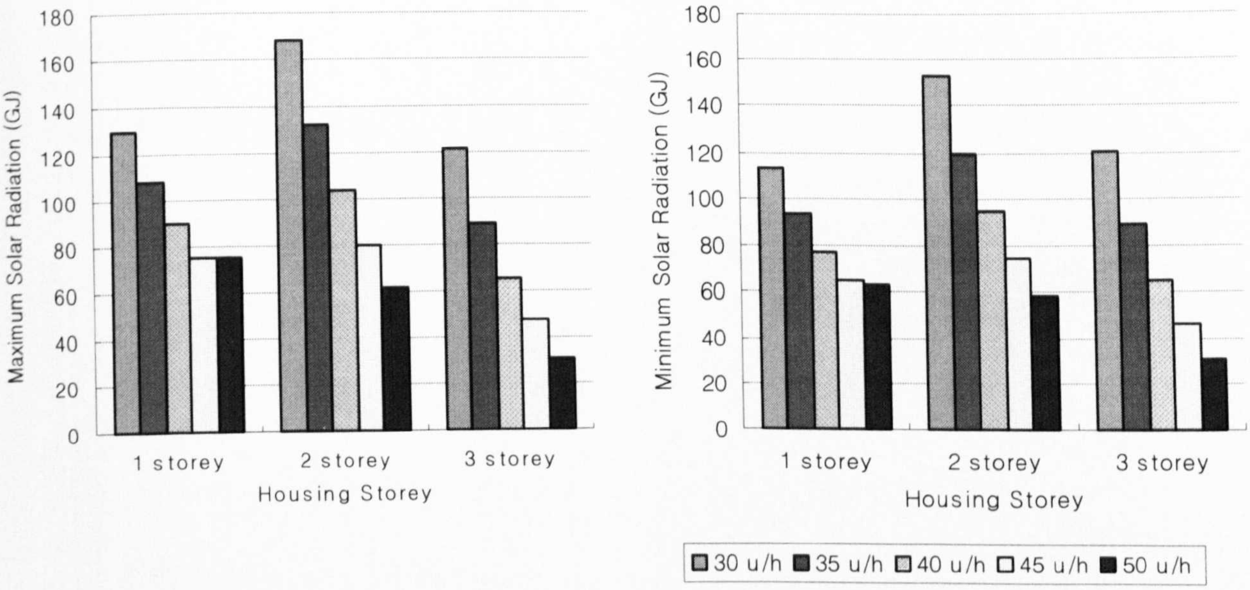


Figure 6-15. Winter solar radiation variations for housings of different densities based on changing housing storey in N-S layout with frontage both to east and west

6-1-4. Aspect Ratio and Solar Radiation

In urban housing design, the ratio of the courtyard, i.e. the shape and proportion, primarily influence the amount of solar radiation received on the wall of the courts. The analysis is based on the relationship between the solar radiation variations and a series of $f_{c.max}/d_{c.max}$ ratios, the aspect ratio of courtyard frontage to courtyard depth on the given courtyard areas, Ac, by the changes of the housing layout factors. More detailed studies to the relationship between the courtyard aspect ratio and the corresponding courtyard housing type are dealt in forthcoming section 6-2.

1. By comparing the variations of the $f_{c.max}/d_{c.max}$ ratio in changing the housing layout factors, in general, the values of the aspect ratio of the given courtyard areas increases, i.e. the courtyard form elongated, when the plot size reduces

(the density increases), the plot frontage shortens and the building height becomes taller. This is due to the assumption that plot area allocated is fully utilised to its maximum for forming a courtyard inside housing plot. However, the amounts of corresponding solar radiation increase to a certain level of building height with reducing plot frontage. This implies that careful consideration of the treatment of courtyard dimension, together with care to secure adequate courtyard area, can be a main design option to control solar gain.

2. Regard should be placed to the relationship between the aspect ratio and the amount of solar radiation and density variations. For example, the density band of 30 units/hectare corresponding to the ratio variations of 1:1.59 - 1.11:1 indicates the less solar gain with narrower fluctuations in winter than the density of 35 units/hectare to the ratios of 1:1.41 – 1.45:1 does (Figure 5-1,2). This, in turn, supports the notion that the controllability of solar radiation in the courtyard can be remarkably improved by selecting the appropriate ranges of the courtyard ratio without increasing the size of housing plot – i.e. reducing the average the housing density.

3. It is also interesting to note that in changing the plot dimension, particularly in the parametric variations from f=15 m (ratio: 1:1.29 – 1.88:1) to f=5m (ratio: 1:12.75 – 1:6.27), the corresponding solar radiation patterns are found to fluctuate in rather smaller ranges in between the maximum and the minimum values (Figure 5-3,4). This is due to the reduction of the plot frontages leading to elongation of the courtyard dimension to the N-S direction even if the frontage reduction contributes to ensuring higher useablility of net plot area (Ap) under the building code. However, it appears that the significance of the relationship between the courtyard ratio and the solar radiation pattern becomes less as the building height increases. Therefore, the benefit of winter solar gain by reducing the plot frontage is more obvious in the higher storeys as solar gain increases in proportion to the reduction in the frontage; i.e. the effect of the aspect ratio of courtyard form on solar radiation is greater

in higher storeys.

4. In the comparison of the E-W layout with the N-S layout, in general, it is observed that a certain value of solar gain can be achieved using the lower ratio range in the N-S layout than in the E-W layout (with frontage to south), as the housing density and the number of storey increases. For instance, in the density band of 50 units/hectare for three storey, the E-W layout gives solar gain of 10GJ at the ratio of 0.31-29.41 as the N-S layout attains to the 30GJ solar gain at the ratio of 0.36 – 3.36. Initially, this means the differences between the layouts are based on the fact that the solar gain in relation to CAR is calculated using the maximum and the minimum limitation of the courtyard aspect ratios considering the relationship between the allocated net court area and the net plot area. This also suggests that, higher solar gain is more easily achievable in the N-S layout than the E-W layout thanks to not only higher CAR attainable but also wider choice of the courtyard aspect ratio available in the N-S layout. Therefore, the analyses imply that the N-S housing layout planning can provide great flexibility about compromising efficient land-use by considering the density and solar gain with other factors such as functional and aesthetic requirements.

6-1-5. Implication of the Analyses for Passive Urban Courtyard Design Strategies

To draw a conclusion initially, the implication of the analyses has been inspiring by suggesting that increasing building height does not always relate to the reduction of the solar gain received inside courtyard. In addition, designers must understand how the design parameters such as plot dimensions and courtyard shapes and proportions contribute to solar gain in the courtyard. To support this, V. Olygay (1963) and Ho (1996) explained the importance of the relationship between the local climate conditions and building forms. It was stressed that the building dimension played an important role in controlling solar radiation efficiently in designing the building forms in the context of true regional forms. This, in turn, may generate a courtyard form, which maintains a relatively high density and achieves adequate amounts of solar radiation through the process of analytical selection and adaptation of the factors such as plot location, dimension and courtyard ratio.

De Chiara (1984) mentions the beneficial effects of adapting the urban courtyard house. He describes that, when used as an attached house, the type of house such as a courtyard house has long been advocated for urban families with children as a detached single-family house and the economic necessity of multifamily units. The courtyard house, which makes maximum use of the space and can be located on a much narrower plot than a conventional detached house, also provides maximum privacy and livability. Consequently, these all together necessitate the introduction of a compact courtyard housing form that can accommodate such a wide range of requirement of an urban environment mentioned above.

Broadly speaking, it has been an established fact that, of course, a low-rise building in an average low-density development could provide a ideal solution for controlling and achieving a certain amounts of solar radiation objective in the courtyard. But, at the same time, it is also very important to take land-use intensity in terms of one of the urban environment requirement into account. All the above analyses confirm that low-rise courtyard housings are not always climatic responsive. Through the variations of the housing layout factors such as plot size, plot dimension and plot location, it seems to be possible to maintain adequate amounts of solar radiation in the courtyard of a relatively higher-storey housing whilst achieving the most favorable range of an urban land-use standard as well as functional and aesthetic requirements.

6-2. Recommendations on Urban Climatic Responsive Courtyard Housing Design

Here, particular attention is given to general typologies on plans of standard courtyard types related to the variations of the housing layout factors. Of many factors which are of importance to housing layout, the four housing layout factors such as housing density, plot dimension, housing development scale and housing orientation are considered. The aim is to investigate the relationships between the variations of the housing layout factors and a series of generic courtyard types based on the results of considering the relation of net plot area (Ap) to net courtyard area (Ac). Thus, the subsequent results on the relative suitability of the courtyard shape according to the factors illustrated here are used to provide fundamental knowledge to generalise a range of recommended shapes of the courtyard in high density development.

The following criteria have been chosen;
Identification of,
1. The range of courtyard shapes corresponding to variations in the housing layout factors in which, in general, relatively high solar gain is indicated.
2. The range of courtyard shapes corresponding to density change of a housing plot location which is advantageous to achieving higher density and solar gain.

6-2-1. Courtyard Housing Form – Housing Layout Factor and Shape

The main methods of investigation to classify the courtyard shapes corresponding to the housing factor variations include the illustrations of the best possible courtyard dimensions suited within the range of the allocated net plot area (Ap) and its corresponding net courtyard area (Ac) in each range of the individual factors.

To simplify the parameters such as shape and orientation, a few generic types of courtyard housing are chosen with a view to illustrate a reasonably wide range of potential courtyard types. The chosen variations which are to be used to identify the relation of courtyard shape to housing layout variations in terms of suitability are seen in Fig 6-16. In addition, assessments on the suitability of the shape are made on the information that the variations on the minimum dimension of the building block ranges from 1.8m to 3m at intervals of 30cm, i.e. 1.8m, 2.1m, 2.4m, 2.7m and 3m (NBA, 1981). Here, an assumption that the minimum depth of the building block allowed should be 1.8m or over (based on 30cm module) is especially made for the purpose of the study. Although the range has its limitations, it is specific enough to inform early design decisions on the advantages and disadvantages of urban courtyard shapes. It is also assumed that walls are included in the building depth.

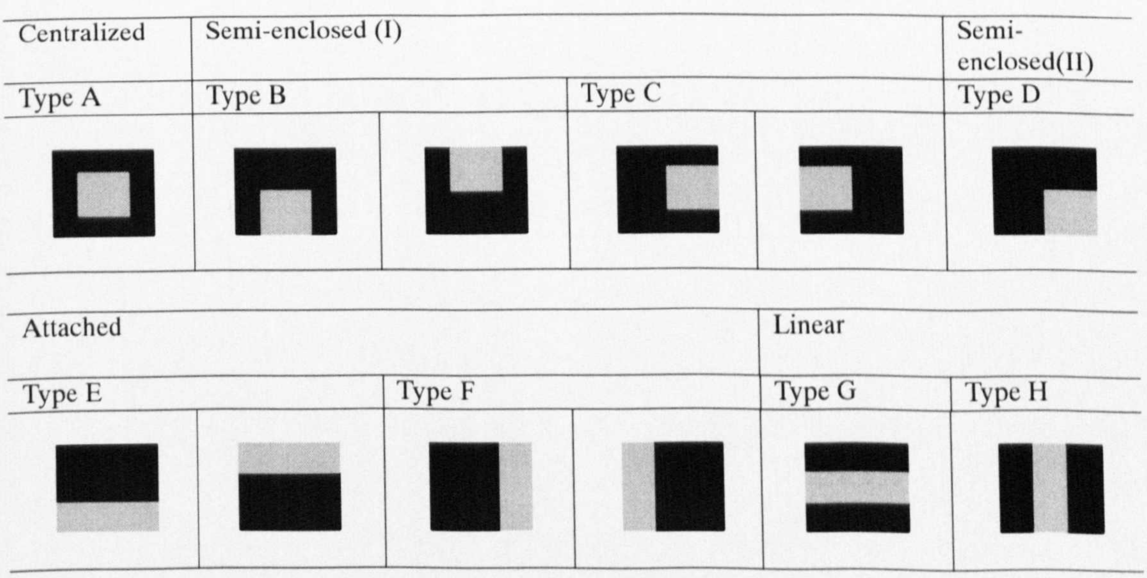


Figure 6-16. Plans of the standard generic courtyard types used in the analyses

In order to identify the most frequently appeared courtyard types for given situation, a series of the graphs shown in chapter 5, which illustrates a set of courtyard floor plans – i.e. courtyard dimensions – corresponding to a given range of the housing layout factor variations, is used. As explained in section 5-1-2, by using each graph as shown in Figure 5-1 for example, four courtyard dimensions under given size of Ac are chosen on a basis of equal division of fc (allocated courtyard frontage), so that the relationship between the courtyard dimension and net plot area (Ap) can be identified. That is, since the dimensions of Ap and Ac are fixed, a range of possible courtyard types can be given with using a series of marginal spaces from the combination of those dimensions. The lists of frequencies of chosen four courtyard dimensions, which is named here as the 'suitability', according to the different generic courtyard types for each housing layout factor are summarised in Appendix 2. These lists are then converted in terms of the suitability of the generic courtyard types based on the variations in the housing layout factors, which are shown in Table 6-1 ~ 14.

In order to decide possible plans among the plans of the standard generic types, the list of criteria based on the minimum building block depth of 1.8m, is as follows.

For both given plot frontage and depth directions,

1. If both the total and the half of the marginal spaces between the boundaries of plot and courtyard are over 1.8m, then either one or two building blocks can be accommodated in given spacing.
2. If the total of marginal space is over 1.8m but the half of the space is less than 1.8m, then only one building block can be accommodated in given spacing.
3. If both the total and the half of marginal space are less than 1.8m, then no building block can be accommodated in given spacing.

The following pages demonstrate the courtyard types according to the housing layout factors in detail based on Table 6-1 ~14, which express the results in a mere readily understandable visual form.

6-2-1-1. Courtyard type and housing density factor

It appears that the housing shape responds significantly to the variations of the housing density in housing layout with E-W with frontage to south. The corresponding shapes to the density variation based on a series of possible courtyard dimensions, which is produced within the allocated ranges of Ap and Ac in each of the factors, are stated in consideration of both density and building height variations in this section. According to this, in the variations of allocated courtyard dimensions in each of housing density bands, the most common shapes frequently appeared are the 'attached' and 'semi-enclosed II' courtyards (types D, E and F).

In addition, the choice of courtyard type based on the relative suitability on the relationship between the shape and the density variation is reported in Table 6-1, 2 and 3.

CF/BF = courtyard floor area to main ground building floor area
**: Most frequent type of courtyard shape appearing in each housing density band of the housing density factor for the housing layout E-W with frontage to south
*: Secondary type of courtyard shape in each housing density band

① Housing density; 30 units/hectare
1 storey: CF/BF = 3.03:1, **attached (type E and F) and linear (type G and H)
2 storey: CF/BF = 2.8:1, **attached (type E); *semi-enclosed II (type D), attached (type F) and linear (type G and H)
3 storey: CF/BF = 2.11:1, **attached (type E and F); *linear (G and H)

② Housing density; 35 units/hectare
1 storey: CF/BF = 2.32:1, **attached (type E); *semi-enclosed (II), attached (type F) and linear (type G and H)
2 storey: CF/BF = 2.09:1, **attached (type E); *semi-enclosed (II), attached (type E) and linear (type G and H)
3 storey: CF/BF = 1.4:1, **semi-enclosed II (type D); *semi-enclosed I (type B),

attached (type E and F) and linear (type G and H)

③ Housing density; 40 units/hectare

1 storey: CF/BF = 1.78:1, **semi-enclosed II (type D), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.56:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.86:1, **semi-enclosed II (type D); *semi-enclosed I(type B), attached (type E and F) and linear (type G and H)

④ Housing density; 45 units/hectare

1 storey: CF/BF = 1.37:1, **semi-enclosed II (type D); *semi-enclosed I(type B), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.14:1, **semi-enclosed II (type D); *semi-enclosed I(type B), attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.45:1, **semi-enclosed II (type D), semi-enclosed I (type B and C); * attached (type E and F) and linear (type G and H)

⑤ Housing density; 50 units/hectare

1 storey: CF/BF =1.04:1, **semi-enclosed II (type D); *semi-enclosed (I (type B and C), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 0.81:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.11:1, **semi-enclosed I (type B and C), semi-enclosed II (type D); *attached (type E and F) and linear (type G and H)

6-2-1-2. Courtyard type and plot dimension factor

The types of courtyard shape mostly appearing in relation to the plot dimension variation are 'attached' (type E and F) and 'linear' (type G and H).

Here, further details of the courtyard shape ranges by increasing plot frontage are shown below. The results on the relative suitability of courtyard shape related to the frontage variation are summarised in Table 6-4, 5 and 6.

CF/BF = courtyard floor area to main ground building floor area

**: Most frequent type of courtyard shape appearing in each plot frontage band of the plot dimension factor for the housing layout E-W with frontage to south

*: Secondary type of courtyard shape in each plot dimension band

① Plot dimension; 5m

1 storey: CF/BF = 2.34:1, **attached (type E) and linear (type G)

2 storey: CF/BF = 2.27:1, **attached (type E) and linear (type G)

3 storey: CF/BF = 2.04:1, **attached (type E) and linear (type G)

② Plot dimension; 10m

1 storey: CF/BF = 2.06:1, **attached (type E) and linear (type G); *semi-enclosed II (type D) and attached (type F)

2 storey: CF/BF = 1.92:1, **attached (type E) and linear (type G); *attached (type D), semi-enclosed II (type D)

3 storey: CF/BF = 1.45:1, **attached (type E) and linear (type G); *attached (type F) and linear (type H), semi-enclosed II (type D)

③ Plot dimension; 15m

1 storey: CF/BF = 1.79:1, **semi-enclosed II (type D); *attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.56:1, **semi-enclosed II (type D); *semi-enclosed I (type B) and attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.86:1, **semi-enclosed I (type B and C) and semi-enclosed II (type D); *attached (type E and F) and linear (type G and H)

④ Plot dimension; 20m

1 storey: CF/BF = 1.5:1, **attached (type F) and linear (type H); *semi-enclosed

II (type D), attached (type E)

2 storey: CF/BF = 1.2:1, **attached (type F) and linear (type H); *semi-enclosed II (type D) and attached (type E)

3 storey: CF/BF = 0.28:1, **semi-enclosed I (type B), semi-enclosed II (type D); *attached (type E and F) and linear (type H)

⑤ Plot dimension; 25m

1 storey: CF/BF = 1.22:1, **attached (type F) and linear (type H); *semi-enclosed I (type B), semi-enclosed II (type D) and attached (type E)

2 storey: CF/BF = 0.85:1, **attached (type F) and linear (type H); *semi-enclosed I (type B), semi-enclosed II (type D) and attached (type E)

3 storey: Not applicable

6-2-1-3. Courtyard type and housing development scale factor

In general, 'semi-enclosed II' (type D) – housings with L-shape courtyard – are found to occur as the most appearing types as long as the variation of housing scale factor is concerned here. Further detail on the shapes of each housing unit band is shown below. The relationships of courtyard shape and the number of housing units in the light of the relative suitability are illustrated in Table 6-7, 8 and 9.

CF/BF = courtyard floor area to main ground building floor area

**: Most frequent type of courtyard shape appearing in each housing unit band of the housing development factor for the housing layout E-W with frontage to south

*: Secondary type of courtyard shape in each housing unit band

① Housing development scale; 50 units and 100 units

1 storey: CF/BF = 1.76:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached(type E and F) and linear (type G and H)

2 storey: CF/BF = 1.54:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached(type E and F) and linear (type G and H)

3 storey: CF/BF = 0.84:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

② Housing development scale; 500 units and 1000 units

1 storey: CF/BF = 1.79:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.56:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.86:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

③ Housing development scale; 1500 units

1 storey: CF/BF = 1.78:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.55:1, **semi-enclosed II (type D); *semi-enclosed I (type B), attached (type E) and linear (type G)

3 storey: CF/BF = 0.85:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

6-2-1-4. Courtyard type and housing orientation factor (facing E-W street with frontage to north)

'Semi-enclosed II' (type D) and 'attached' (type E) are those of courtyard shapes most frequently appeared in the housing density variations for E-W layout with frontage to north. Corresponding shapes to each housing density band are shown below. The relationships of courtyard shape and the housing density are indicated in Table 6-10 and 11.

CF/BF = courtyard floor area to main ground building floor area

**: Most frequent type of courtyard shape appearing in each housing density band of the housing orientation factor for the housing layout E-W with frontage to north

*: Secondary type of courtyard shape in each housing density band

① Housing density; 30 units/hectare

1 and 2 storey: CF/BF = 3.25:1, **attached (type E and F); *linear (type G)

3 storey: CF/BF = 3.13:1, **attached (type E and F); *linear (type G and H)

② Housing density; 35 units/hectare

1and 2 storey: CF/BF = 2.54:1, **attached (type E); *attached (type F) and linear (type G and H)

3 storey: CF/BF = 2.42:1, **attached (type E); *semi-enclosed (type D), attached (type F) and linear (type G and H)

③ Housing density; 40 units/hectare

1 and 2 storey: CF/BF = 2.01:1, **attached (type E); *semi-enclosed II (type D), attached (type F) and linear (type G and H)

3 storey: CF/BF = 1.88:1, **attached (type E); *semi-enclosed II (type D), attached (type F) and linear (type G and H)

④ Housing density; 45 units/hectare

1 and 2 storey: CF/BF = 1.59:1, **semi-enclosed II (type D); semi-enclosed (type B), attached (type E and F), linear (type G and H)

3 storey: CF/BF = 1.47:1, **semi-enclosed II (type D); semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

⑤ Housing density; 50 units/hectare

1 and 2 storey: CF/BF =1.26:1, **semi-enclosed II (type D); semi-enclosed (type B), attached (type E and F), linear (type G and H)

3 storey: CF/BF = 1.13:1, **semi-enclosed II (type D); semi-enclosed I (type B), attached (type E and F) and linear (type G and H)

6-2-1-5. Courtyard type and housing orientation factor (N-S street)

Courtyard shapes frequently appearing as a result of changing housing density in the N-S layout are dealt in here. Corresponding shapes to each housing density band are shown below. The most common shapes frequently appeared are the 'attached' and 'semi-enclosed II' courtyards (types D, F and H). (Table 6-12, 13 and 14).

CF/BF = courtyard floor area to main ground building floor area

**: Most frequent type of courtyard shape appearing in each housing density band of the housing density factor for the housing layout N-S

*: Secondary type of courtyard shape in each housing density band

① Housing density; 30 units/hectare

1 storey: CF/BF = 2.97:1, **attached (type F); *semi-enclosed II (type D), attached (type E) and linear (type H)

2 storey: CF/BF = 2.69:1, **attached (type F) and linear (type H); *semi-enclosed II (type D) and attached (type E)

3 storey: CF/BF = 1.87:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

② Housing density; 35 units/hectare

1 storey: CF/BF = 2.31:1, **attached (type H); *semi-enclosed II, attached (type E) and linear (type G and H)

2 storey: CF/BF = 2.07:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

3 storey: CF/BF = 1.38:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

③ Housing density; 40 units/hectare

1 storey: CF/BF = 1.81:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

2 storey: CF/BF = 1.61:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

3 storey: CF/BF = 1.01:1, **attached (type F) and linear (type H); *semi-enclosed II (type D), attached (type E) and linear (type G)

④ Housing density; 45 units/hectare

1 storey: CF/BF = 1.42:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 1.25:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H

3 storey: CF/BF = 0.72:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

⑤ Housing density; 50 units/hectare

1 storey: CF/BF = 1.11:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

2 storey: CF/BF = 0.96:1, **semi-enclosed II (type D); *semi-enclosed I (type B and C), attached (type E and F) and linear (type G and H)

3 storey: CF/BF = 0.49:1, **semi-enclosed I (type B) and semi-enclosed II (type D); *semi-enclosed I (type C), attached (type E and F) and linear (type G and H)

6-2-2. Courtyard Shape Characteristics reflected by High Urban Density

Based upon the Tables 6-1 ~ 14 expressing visual representations of the relative suitability of courtyard shape to each of the housing layout factors, this section attempts to detail a range of courtyard shapes complying with the variation of the housing layout factors, namely plot dimension and orientation etc, especially in high density development. First of all, the degree of the sensitivity on the form of the courtyard shape to the variation of the housing layout factor and the building height is analysed. Then, the generalised results of the study on the suitability and the sensitivity are put together to make a list of the salient features, which is obvious to viewer, of each of the courtyard shapes.

6-2-2-1. Effect of housing layout factor on courtyard shape

Focusing on the relationship between the housing factor and the courtyard shape, analyses are carried out from the viewpoint of the effect of housing layout factor on variations in the shapes regardless of the change of building height. Accordingly, courtyard shapes with a tendency of relatively frequent appearance by varying the factor are chosen and mentioned in lieu of embodying courtyard shape generalisations.

① Housing density factor (Housing layout with parallel street E-W with frontage to south)

It has been found that, in general, housing shapes such as semi-enclosed I (type B and C) and semi-enclosed II courtyards (type D) and attached courtyards (type E and F) become more sensitive than the other types by showing wider housing variations in the range of the density factor. In other words, the suitability of semi-enclosed I & II types particularly increases with the increase of density, whilst those of attached types markedly decreases. The effects of changing density on the variations in the suitability of linear courtyards (type G and H) are found to be negligible.

② Plot dimension factor (Housing layout with parallel street E-W with frontage to south)

The suitability of semi-enclosed I & II types becomes reduced and those of attached and linear (open east-west axis) increased as the frontage of a plot reduces, i.e. the net plot area (Ap) increases.

③ Housing development scale factor (Housing layout with parallel street E-W)

By merely increasing in the number of housing units, the variations in the suitability of the generic courtyard types remain nearly constant except that small rises in the suitability of attached and linear (open north-south axis) type are noticeable in a limited range

④ Housing orientation factor (Housing layout with parallel street E-W with frontage to north)

Changing plot orientation with frontage to north in the E-W layout, the suitability of those courtyards of semi-enclosed I (type B) and semi-enclosed II (type D) increase as density increases. On the other hand, the suitability of attached courtyard (type E and F) seems to decrease whilst the effect of changing density on the variations in those of semi-enclosed I (type C) and linear (type G and H) is insignificant.

⑤ Housing orientation factor (Housing layout with parallel street N-S)

In a housing layout with housing frontage facing parallel street running N-S, courtyard types of semi-enclosed I & II have relatively high sensitivity to the variations in the density change, thereby demonstrating an increase in suitability. But, the types of attached and linear (open north-south axis: type F and H), which also show high sensitivity as in the case of the semi-enclosed, decrease in suitability. The density change for attached and linear courtyards (open east-west axis: type E and G) doesn't make any prominent feature in terms of sensitivity.

6-2-2-2. Effect of building height on courtyard shape

It is interesting to compare the above observations, which is related to the sensitivity analyses of courtyard shape variations focusing on changing the housing layout factors, with the analyses on changing building height in general. In looking at these analyses a number of general features can be identified on the basis of the housing layout factors.

① Housing density factor (Housing layout with parallel street E-W with frontage to south)

Increasing the number of building stories, the suitability of semi-enclosed II courtyards remain relatively constant, there are overall increases in the suitability of semi-enclosed I courtyards. It is also shown that the suitability of both types of linear courtyards (east-west and north-south axis: type G and H) hold the same in term of sensitivity indicating moderate suitability.

② Plot dimension factor (Housing layout with parallel street E-W with frontage to south)

For most of the courtyard shapes, the variations of suitability so fluctuate that general trends seem to be obvious only in a limited range of courtyard shapes such as the 'attached' together with 'linear' courtyards (type E, F, G and H). That is, the suitability of those types remain nearly constant with increasing building height, thereby suggesting the change of the building height doesn't affect the range of suitability much.

③ Housing development scale factor (Housing layout with parallel street E-W with frontage to south)

In the housing development scale factor, semi-enclosed I courtyards (open to the south and the north: type B) has the potential of increasing the suitability by increasing building height, as most of the other types have the least shape suitability.

④ Housing orientation factor (Housing layout with parallel street E-W with frontage to north)

Unlike the patterns of suitability indicated for E-W layout to south, the variations in courtyard shape in E-W layout to north remains mainly constant regardless of changing building height. Accordingly, there is no significant effect of changing the height on any type of courtyard shapes.

⑤ Housing orientation factor (Housing layout with parallel street N-S)

Compared to the housing layout with E-W streets, the features of the effect of changing building height in each density band with the courtyard shape suitability are somewhat different. The analyses regarding the common features most obvious indicate that there are no significant effects of changing the height on the shape suitability except semi-enclosed I and linear courtyards (type B, C, G and H) which have small suitability swings.

6-2-2-3. Summary: Adaptibility of courtyard shape to urban residential density

On the basis of the analyses described above, adaptability of each of the courtyard shapes to urban housing development is examined. Therefore, particular attention is given to certain shapes with a potential to form urban courtyard housings taking account of housing layout factors. However, of all the factors, the housing development scale factor does not demonstrate any significant result in terms of sensitivity or suitability, and is therefore excluded.

(i) In general, when compared with attached and linear courtyards, courtyards with semi-enclosed I & II shapes appear to be more appropriate as the density and the building height become higher. This contradicts the general notion that compact courtyard housing forms such as linear or attached shapes are more advantageous in high-density developments than those of the semi-enclosed shape. In fact, it is interesting to discover that this is due to the assumption that the minimum building depth for the urban courtyard housing design should be 1.8m or over. Namely, high density housing has more efficient use of space for certain options of courtyard types such as semi-enclosed I & II shapes than low density housing in terms of optimising plot use. Moreover, in low-density housing, the housing dimension required to fit the shape makes house building of this type impractical.

(ii) Semi-enclosed (I) courtyards: The overall suitability of these housing types, on the whole, increases as density increases for the both layout. In the E-W layout, all of the semi-enclosed shapes open to all directions – i.e. east, west, south and north- have a potential of increasing frequency of appearance with even suitability in high-density band especially for two and three storeys. However, in the N-S layout, semi-enclosed shapes open to south/north (type B) tend to appear as more appropriate options by showing higher degree of suitability than courtyards to east/west (type C). Broadly speaking, in consideration for the results and analyses discussed in the previous section that the higher amounts of solar radiation can be achievable in the N-S layout, particularly in high density, the need for the application of Type B courtyards to the N-S layout is emphasised.

(iii) Semi–enclosed (II) courtyards: As is the case with semi-enclosed I, these types of courtyard shape (type D) prove to be susceptible to the variations in housing density regardless of plot orientation. Type D courtyard seems to be more suitable option as density increases and the number of building storey raised. In terms of reducing plot frontage to obtain appreciable amounts of solar radiation, semi-enclosed II (type D) might be a better option for relatively narrow frontage than the other types

(iv) Attached courtyards: Although these types of courtyard shape (type E and F) seem to be less considerable options compared to Type B and Type D courtyards for any type of the plot orientations, these types might be still useful as viable one in situations where requiring alternative design option is required. In general, Type E courtyard (east-west axis) might be introduced into the E-W layout as a secondary option whilst Type F (north-south axis) seem to be preferred to Type E for the N-S layout. It is also noticeable that attached courtyard shapes might be preferred to semi-enclosed shapes when plot frontage becomes narrow.

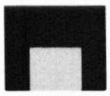
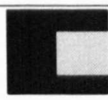
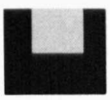
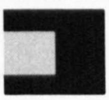
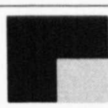
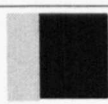
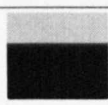
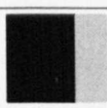
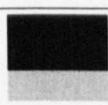
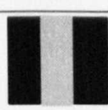
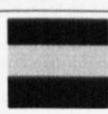
(v) Linear courtyards: All of linear courtyards (type G and H) whose pattern of variations in suitability are similar to those of attached courtyards become less sensitive to the building height variation with increasing density in both street layouts. Type G (east-west axis) courtyard seems to be a reasonable option for the E-W layout, as Type H (north-south axis) is the option for the N-S layout.

Besides, along with the attached courtyards, choice of the linear courtyards can be beneficial than semi-enclosed courtyards especially in narrow frontage bands.

In summary, for high density developments, those semi-enclosed courtyards can be more appropriate than other types of courtyard as long as a suitable limitation on building depth is applied. In particular, those of Type B (semi-enclosed I; facing south and north) and Type D (semi-enclosed II) should be preferred in the N-S layout, regardless of the change of plot orientations, for urban housing developments where courtyard housing design is required. In other words, those solar gains acquired and used in the analyses for the N-S layout have been attained mainly by those courtyard shapes such as Type B and D.

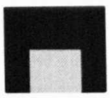
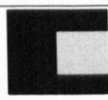
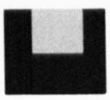
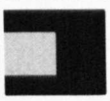
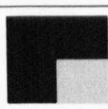
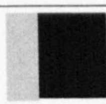
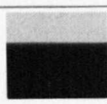
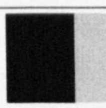
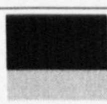
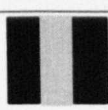
In addition, where narrow frontages for plot dimension is introduced, those attached and linear courtyard, along with semi-enclosed II as secondary choice, will provide better sunlight inclusion. As stated above, the effects of elongating a housing plot to its N-S axis in the E-W layout is related to suitability increase of attached and linear courtyard shapes such as Type E (east-west axis) and Type G (east-west axis). This, in turn, implies that those of Type F and H (both north-south axis) can be the most suitable options for N-S layout as frontage is reduced, by elongating the plot to its E-W axis. A study of the relationship between courtyard design and solar radiation suggests that attached and linear courtyards with running east-west axis seem to be the worst performers giving the least solar gain in winter among the range of shapes and proportions of courtyard housing – at moderately low area ratios they combine heat gain in summer with poor sun light in winter. However, attached and linear courtyards with north-south axis provide relatively even performance year round, and, especially, offer efficient protection from the sun at high density (Pitts et al, 1997). By considering the fact that linear and attached courtyards with north-south axis can be the better optimised choice of courtyard shape for N-S street layouts with reduced frontage, all the above analyses confirm that the N-S street layout is climatically responsive not only in providing better design solution for solar admission but in accommodating better courtyard shapes at high density.

**Table 6-1: Ranking of the generic courtyard types: Housing Density
E-W street with frontage to south: 1 storey**

Plan of the Standard generic courtyard types \ Housing Density		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		●	●	●	●●	●●
		●	●	●	●	●
		●	●	●	●●	●●
		●	●	●	●	●
Semi-enclosed (II)		●	●●	●●●	●●●	●●●
Attached (I) & (II)		●●●	●●	●●	●●	●●
		●●●	●●●	●●	●●	●●
		●●●	●●	●●	●●	●●
		●●●	●●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●

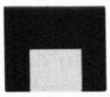
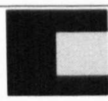
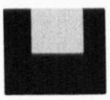
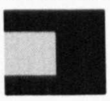
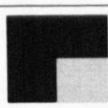
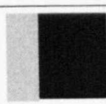
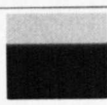
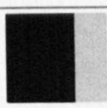
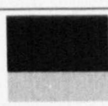
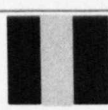
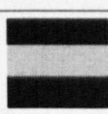
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-2: Ranking of the generic courtyard types: Housing Density
E-W street with frontage to south: 2 storey

Plan of the Standard generic courtyard types \ Housing Density		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		●	●	●●	●●	●●
		●	●	●	●	●●
		●	●	●●	●●	●●
		●	●	●	●	●●
Semi-enclosed (II)		●●	●●	●●●	●●●	●●●
Attached (I) & (II)		●●	●●	●●	●●	●●
		●●●	●●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●●	●●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●

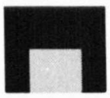
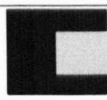
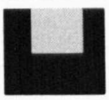
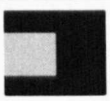
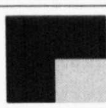
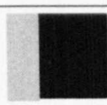
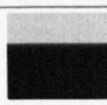
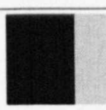
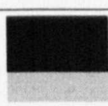
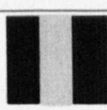
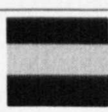
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-3: Ranking of the generic courtyard types: Housing Density
E-W street with frontage to south: 3 storey

Plan of the Standard generic courtyard types \ Housing Density		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		●	●●	●●	●●	●●●
		●	●	●	●●	●●●
		●	●●	●●	●●	●●●
		●	●	●	●●	●●●
Semi-enclosed (II)		●●	●●●	●●●	●●●	●●●
Attached (I) & (II)		●●	●●	●●	●●	●●
		●●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●●	●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●

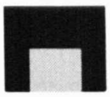
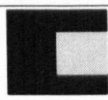
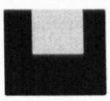
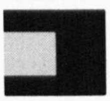
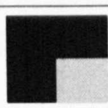
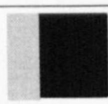
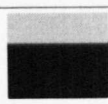
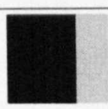
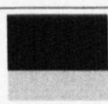
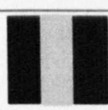
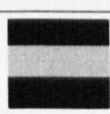
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-4: Ranking of the generic courtyard types: Plot Dimension E-W street with frontage to south: 1 storey

Plan of the Standard generic courtyard types \ Plot Dimension		5 m	10 m	15 m	20 m	25 m
Semi-enclosed (I)		•	•	•	•	••
		•	•	•	•	•
		•	•	•	•	••
		•	•	•	•	•
Semi-enclosed (II)		•	••	•••	••	••
Attached (I) & (II)		•	••	••	•••	•••
		••••	•••	••	••	••
		•	••	••	•••	•••
		••••	•••	••	••	••
Linear (I) & (II)		•	•	••	•••	•••
		••••	•••	••	•	•

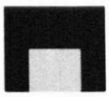
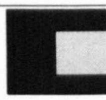
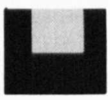
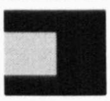
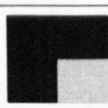
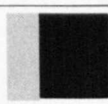
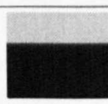
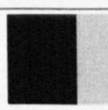
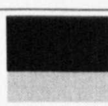
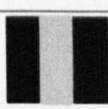
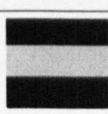
Suitability: • Low
•• Medium
••• High
•••• Very high

Table 6-5: Ranking of the generic courtyard types: Plot Dimension E-W street with frontage to south: 2 storey

Plan of the Standard generic courtyard types	Plot Dimension	5 m	10 m	15 m	20 m	25 m
Semi-enclosed (I)		•	•	••	•	••
		•	•	•	•	•
		•	•	••	•	••
		•	•	•	•	•
Semi-enclosed (II)		•	••	•••	••	••
Attached (I) & (II)		•	••	••	•••	•••
		••••	•••	••	••	••
		•	••	••	•••	•••
		••••	•••	••	••	••
Linear (I) & (II)		•	•	••	•••	•••
		••••	•••	••	•	•

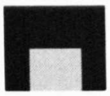
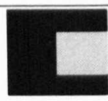
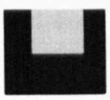
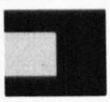
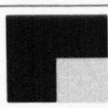
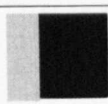
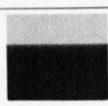
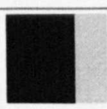
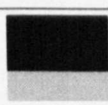
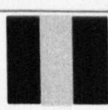
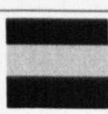
Suitability: • Low
•• Medium
••• High
•••• Very high

**Table 6-6: Ranking of the generic courtyard types: Plot Dimension
E-W street with frontage to south: 3 storey**

Plan of the Standard generic courtyard types \ Plot Dimension		5 m	10 m	15 m	20 m	25 m
Semi-enclosed (I)		•	•	••	•••	•
		•	•	••	•	•
		•	•	••	•••	•
		•	•	••	•	•
Semi-enclosed (II)		•	••	•••	•••	•
Attached (I) & (II)		•	••	••	••	•
		••••	•••	••	••	•
		•	••	••	••	•
		••••	•••	••	••	•
Linear (I) & (II)		•	••	••	••	•
		••••	•••	••	•	•

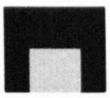
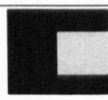
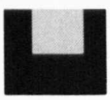
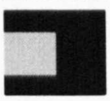
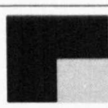
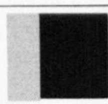
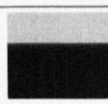
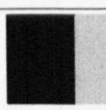
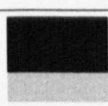
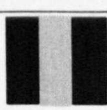
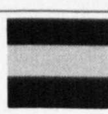
Suitability: • Low
•• Medium
••• High
•••• Very high

Table 6-7: Ranking of the generic courtyard types: Housing development scale E-W street with frontage to south: 1 storey

Plan of the Standard generic courtyard types \ Housing Development Scale		50 units	100 units	500 units	1000 units	1500 units
Semi-enclosed (I)		●●	●●	●●	●●	●●
		●	●	●	●	●
		●●	●●	●●	●●	●●
		●	●	●	●	●
Semi-enclosed (II)		●●●	●●●	●●●	●●●	●●●
Attached (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●

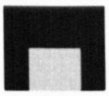
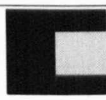
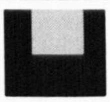
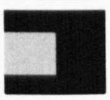
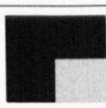
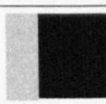
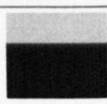
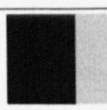
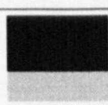
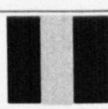
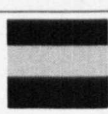
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-8: Ranking of the generic courtyard types: Housing Development Scale E-W street with frontage to south: 2 storey

Plan of the Standard generic courtyard types \ Housing Development Scale		50 units	100 units	500 units	1000 units	1500 units
Semi-enclosed (I)		●●	●●	●●	●●	●●
		●	●	●	●	●
		●●	●●	●●	●●	●●
		●	●	●	●	●
Semi-enclosed (II)		●●●	●●●	●●●	●●●	●●●
Attached (I) & (II)		●●	●●	●●	●●	●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●
		●●	●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●
		●●	●●	●●	●●	●●

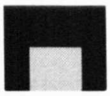
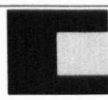
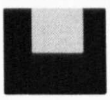
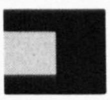
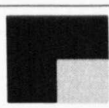
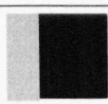
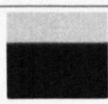
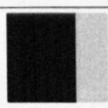
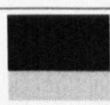
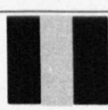
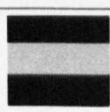
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-9: Ranking of the generic courtyard types: Housing Development Scale E-W street with frontage to south: 3 storey

Housing Development Scale / Plan of the Standard generic courtyard types		50 units	100 units	500 units	1000 units	1500 units
Semi-enclosed (I)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
Semi-enclosed (II)		●●●	●●●	●●●	●●●	●●●
Attached (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●
Linear (I) & (II)		●●	●●	●●	●●	●●
		●●	●●	●●	●●	●●

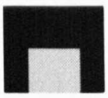
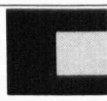
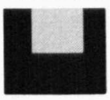
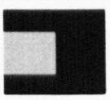
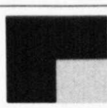
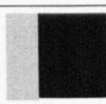
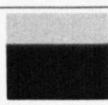
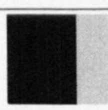
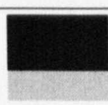
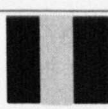
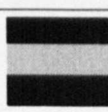
Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-10: Ranking of the generic courtyard types: Housing Orientation E-W street with frontage to north: 1 & 2 storey

Plan of the Standard generic courtyard types	Housing Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		•	•	•	••	••
		•	•	•	•	•
		•	•	•	••	••
		•	•	•	•	•
Semi-enclosed (II)		•	••	••	•••	•••
Attached (I) & (II)		•••	••	••	••	••
		•••	•••	•••	••	••
		•••	••	••	••	••
		•••	•••	•••	••	••
Linear (I) & (II)		•	••	••	••	••
		••	••	••	••	••

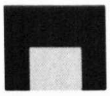
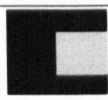
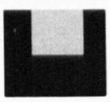
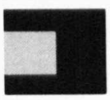
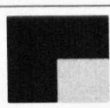
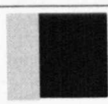
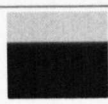
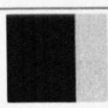
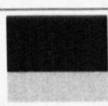
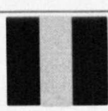
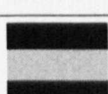
Suitability: • Low
•• Medium
••• High
•••• Very high

Table 6-11: Ranking of the generic courtyard types: Housing Orientation E-W street with frontage to north: 3 storey

Plan of the Standard generic courtyard types \ Housing Density		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		•	•	•	••	••
		•	•	•	•	•
		•	•	•	••	••
		•	•	•	•	•
Semi-enclosed (II)		•	••	••	•••	•••
Attached (I) & (II)		•••	••	••	••	••
		•••	•••	•••	••	••
		•••	••	••	••	••
		•••	•••	•••	••	••
Linear (I) & (II)		••	••	••	••	••
		••	••	••	••	••

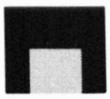
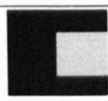
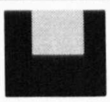
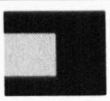
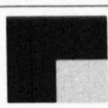
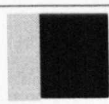
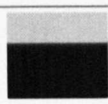
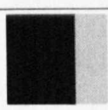
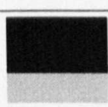
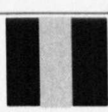
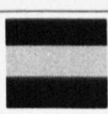
Suitability: • Low
•• Medium
••• High
•••• Very high

Table 6-12: Ranking of the generic courtyard types: Housing Orientation N-S street: 1 storey

Plan of the Standard generic courtyard types \ Housing Density		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		•	•	•	••	••
		•	•	•	••	••
		•	•	•	••	••
		•	•	•	••	••
Semi-enclosed (II)		••	••	••	•••	•••
Attached (I) & (II)		•••	•••	•••	••	••
		••	••	••	••	••
		•••	•••	•••	••	••
		••	••	••	••	••
Linear (I) & (II)		••	••	•••	••	••
		•	••	••	••	••

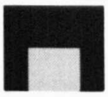
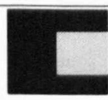
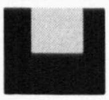
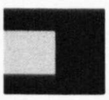
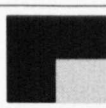
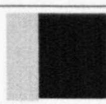
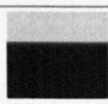
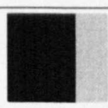
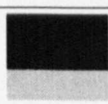
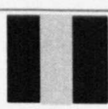
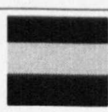
Suitability: • Low
•• Medium
••• High
•••• Very high

Table 6-13: Ranking of the generic courtyard types: Housing Orientation N-S street: 2 storey

Plan of the Standard generic courtyard types	Housing Density	30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		●	●	●	●●	●●
		●	●	●	●●	●●
		●	●	●	●●	●●
		●	●	●	●●	●●
Semi-enclosed (II)		●●	●●	●●	●●●	●●●
Attached (I) & (II)		●●●	●●●	●●●	●●	●●
		●●	●●	●●	●●	●●
		●●●	●●●	●●●	●●	●●
		●●	●●	●●	●●	●●
Linear (I) & (II)		●●●	●●●	●●●	●●	●●
		●	●●	●●	●●	●●

Suitability: ● Low
●● Medium
●●● High
●●●● Very high

Table 6-14: Ranking of the generic courtyard types: Housing Orientation N-S street: 3 storey

Housing Density / Plan of the Standard generic courtyard types		30 units/hectare	35 units/hectare	40 units/hectare	45 units/hectare	50 units/hectare
Semi-enclosed (I)		•	•	•	••	•••
		•	•	•	••	••
		•	•	•	••	•••
		•	•	•	••	••
Semi-enclosed (II)		••	••	••	•••	•••
Attached (I) & (II)		•••	•••	•••	••	••
		••	••	••	••	••
		•••	•••	•••	••	••
		••	••	••	••	••
Linear (I) & (II)		•••	•••	•••	••	••
		••	••	••	••	••

Suitability: • Low
•• Medium
••• High
•••• Very high

Summary of the Chapter

Through the evaluation and re-interpretation of the analyses of the urban courtyard housing models on the basis of the height variations, a range of possible solutions for optimising courtyard design for solar radiation is suggested in two categories; efficient urban layout planning and courtyard housing form.

For efficient layout planning in urban development, interdependent design objectives for achieving high land-utilisation with maintaining better solar access inside courtyard facades are; (1) provide better chances of utilising land-use by careful consideration of plot geometry. (2) make provisions for solar heat gains by judicious combination of plot size and plot frontage. (3) adopt efficient and climatic responsive design strategies by introducing a layout of parallel street N-S.

In terms of courtyard housing form, the question of how far to take the design objectives can be answered only in search of optimising courtyard design corresponding to the efficient urban layout planning. In addition, consider the following measures; (1) make the most use of semi-enclosed courtyard types for high-density development as long as a suitable limitation on building depth is applied. (2) maximise the benefits of solar gain by adopting semi-enclosed types (U and L- shaped) facing south and north into N-S layout. (3) Utilise attached and linear types (north-south axis) as secondary choice where narrow frontages are applicable in N-S layout.

Designers and planners have only little concern for the implications of land-utilisation and solar radiation for passive solar housing. Where applicable, a systematic procedures should be applied in order to evaluate passive design quality in the course of design.

Chapter 7

Conclusion

7-1. Summary of the Thesis

In conventional detached housing design, it has been general notion that building forms with a relatively low density development could play such a dominant role in ensuring solar access so much so that low-rise buildings have been considered as a solution for passive building design. However, by considering conditions in urban housing layouts where particular requirements for higher density should be met, the introduction of low-rise forms will conflict with the objective of efficient land-utilisation. Accordingly, a need arises to introduce a form, which can provide maximum land-use among urban detached house types as well as create comfortable environments by minimising loss in sunlight. Apart from being one of the most preferred housing forms based on the national housing distribution survey in Korea, the potential of the courtyard housing form should be investigated in terms of climatic responsive urban housing design.

As Korean land-use policy relating housing designs provides more complex situations for architects to deal with, this study includes an evaluation of the current building regulation codes available, in terms of their applicability to land-use for courtyard housing developments. The brief summary of the thesis is as follows.

After the introduction chapter, chapter 2 of the thesis reviewed the background studies of Korean housing in relation to its physical environment focusing on the climatic conditions. In order to derive the criteria of Korean seasonal variations for the methodology adopted here, the general features of the climate condition accompanied by several climatic analysis schemes were determined. Then, a range of general housing types in the context of urban layout pattern was reviewed from the historical viewpoint. Since architects, as well as town planners and local authorities, have been aware increasingly of how traditional buildings have well adapted to physical environments, efforts to demonstrate some of remarkable features in the formation of courtyard housing designs and urban town planning were made. Through information given in this chapter, the need to utilise traditional design techniques arises.

In an effort to develop the density expressions by using the courtyard form in contemporary urban layout developments, a range of constraints on built form needs to be considered including land-use data from current building regulation codes. The selected constraints, setback spacing to front road and north, and community facility allocations, were converted into simple variables for the density expression. Then, simple urban courtyard housing layouts, which showed the performance of housing layout factors (housing density, plot dimension, housing development scale and plot orientation) were modelled. This led to the direct comparison of the housing layout factors for urban courtyard housing design assessment. Therefore, by using the housing models and the density expressions, the relationship between the housing layout factors, and net courtyard area and corresponding solar radiation could be identified.

A computer program tool (Shadowpack package P.C version 2.0) for solar radiation assessments of building facades has been utilised. This is a useful tool to calculate quantitatively the corresponding range of the amount of solar radiation available to courtyard areas as a result of the variations of the housing layout factors in the density expression. In order to help to measure the relative performance of the factors, two subprograms, ICON and SHADEN, have been selected. First, an interactive program, ICON, was used to build a series of 3D courtyard models. Then, SHADEN was operated to embody the amount of solar radiation of the models. The method of application of the programs to the models including the other subprograms has also been mentioned in Chapter 4.

Through the development of a series of density expressions and the establishment of the computer tools, the relative performance of varying the housing layout factors for courtyard area ratio (CAR) and solar radiation were analysed in Chapter 5. A range of results was produced, indicating that the amount of CAR and corresponding solar radiation does vary with the application of the housing layout factor into urban developments, where the courtyard housing design is considered. The results are given based on calculating Ap (net plot area), Ac (net courtyard area), BC (building coverage) and CAR. A range of courtyard plans whose sizes and dimensions were varied based on the a given range of courtyard frontages and depths as well as considering allocated Ap and Ac, were also shown. Generally, the analyses of the first stage show that, whilst CAR steadily decreases with increasing the number of housing storeys, the amount of solar radiation increases up to certain level of building height. Therefore further efforts are required to investigate the implications of building heights on passive solar courtyard housing.

The results were evaluated and re-interpreted, in Chapter 6, with a view to assessing the effect of the height variations on the amount of solar gain within courtyard housing. A range of criteria was considered in order to suggest the advantages and disadvantages of the housing layout factors relating to building height. By these means, special emphasis was placed on efficient urban layout planning and courtyard housing form. For the efficient urban layout form, in order to make most use of solar gain, solutions have been sought in terms of; (1) providing optimised plot geometry, (2) combining the housing layout factors and (3) introducing better plot orientation in relation to street layouts. The comparative and parametric study indicated that by judicious combination of the factors, a certain density objective can be attainable whilst maintaining better solar gain in urban layouts. For the courtyard housing form, the potential of a series of generic courtyard types, which correspond to optimised urban layout form, was examined. Certain forms showed much better potential than others.

7-2. Main Results and Conclusions

This study has been motivated by an assumption that an increase of housing storeys influences overall solar gain in courtyard facades. The main results and conclusions from this study are summarised as below,

1. In general, the study implies that increasing the number of storeys whilst maintaining the same size of ground housing area results in a decrease in net useable courtyard area as well as CAR (courtyard area ratio). However, it should be noted that the amount of solar radiation received on the courtyard facades in summer and winter increases up to certain level of building height based on varying the housing layout factors.

2. The analyses of the overall pattern of the variations in solar radiation indicate that the amounts of winter solar radiation tend to decrease more rapidly than those of summer solar radiation when raising building height from two to three-storey housing whilst maintaining the same size of ground housing area. This is due to the relatively low sun angle in winter period. However it should be noted that general reductions in solar gain start to occur particularly in three-storey housing where bigger setback spacing is allocated from the current building codes. For example, increases of 35 – 40 GJ in solar radiation are recorded by raising from one to two-storey housing, and decreases of 8 – 22 GJ from two to three-storey housing are found with the density of 30 units/hectare for the E-W layout. Accordingly, this clearly indicates that the reduction of the amounts of solar radiation is caused by not only overshadowing effects between courtyard walls, but remarkable reductions of usable net courtyard areas due to the intensified building code application with increasing the height, especially for three-storey housing. As discussed, setback spacing guidelines together with the limitation of building coverage and floor area ratio according the areas designated by the building codes, are introduced to safeguard solar access between a row of adjacent housings for conventional detached housing models. Considering that the courtyard type of house could make maximum use of plots with inward-

directed courts, particular attention should be given to the differentiation of the level of the building code application according to a range of urban housing types. Besides, the differences of solar radiation caused by changing the plot frontage factor between one to three-storey housing are insignificant compared to changing those of the housing density factors. This suggests that increasing the building height does not much affect variations in winter solar radiation when the plot frontage becomes narrower.

3. The t value, which represents the proportion of net plot area (Ap) to total plot area including allocations for community facilities, was introduced since the allocations of the facilities varied with the number of housing units in a development under the building regulation codes. On the assumption that the land-use of the development is maximised by considering the minimum allocation of the community facilities, the effect of the housing development scale factor has been examined by increasing the number of housing units. It was found that, on the whole, the average effects on the summer and the winter solar radiation in relation to the housing development scale factor are negligible compared to the other factors.

4. In an attempt to find out the effect of plot orientations, the study indicates that N-S layout could be more beneficial than E-W layout in terms of achieving a certain density objective whilst maintaining adequate solar gain into the courtyards. That is, increasing housing density causes smaller winter solar radiation swings especially in high-storey ranges – 3 storey – on the N-S layout than on the E-W layouts with frontage both to north and south. For example, for E-W layout with frontage to south, as the density increases from 30 to 50 units/hectare, a decrease of 126 – 128 GJ in the solar radiation occurs. However, for the N-S layout with frontage to both east and west, a reduction of only 88 – 90 GJ occurs, which is about two-thirds of those of the E-W layout to south. The same trend applies to the relationship between the N-S layout and the E-W layout with frontage to north. In addition, the amounts of winter solar radiation of N-S layout reaches higher than those of E-W layout to south especially at high density

bands ranging from 40 to 50 units/hectare as the building height increases (3 storey; 50 unit/hectare; E-W: 10.2 GJ, N-S: 30.9 GJ).

5. Based on the analyses, it is interesting to compare the housing density factor and the plot dimension factor. The change in solar gain is particularly profound in relation to the plot dimension factor, when plot frontage, f, becomes narrower. In other words, decreasing plot frontage seems to be more advantageous in ensuring appropriate amount of solar gain than increasing the size of housing plot. For instance, there are increases of 33.8 – 34.8 GJ in solar gain by decreasing housing density from 40 to 35 units/hectare, resulting in an increase of 36.79 m^2 in net plot area (Ap) for three-storey housing. However, for the same building height, decreasing plot frontage from 15 to 5 m results in a net plot area increase to 27.50 m^2, which causes an increase of about 63 - 63.1GJ. Consequently, by combining housing layout factors judiciously such as plot frontage and plot orientation, it is possible to achieve relatively high density objective in an urban environment, while maintaining better solar access into courtyard housing.

6. As far as urban courtyard design is concerned, in general, when compared with attached and linear courtyards, semi-enclosed courtyard types appear to be a more suitable form, as the density and the building height become higher. This contradicts the general notion that compact courtyard housing forms such as linear or attached shapes are more advantageous for high-density developments than those of the semi-enclosed shape. In fact, this is due to the assumption that a limitation on minimum building depth has been applied in this case, i.e. the minimum depth should be 1.8 m or over. As the housing dimension of low-density housing makes the courtyard type of semi-enclosed shapes relatively impractical, high-density housing has more efficient use of space for certain options of house building of this type in terms of optimising plot use.

7. For the N-S layout, among those of courtyard shapes, semi-enclosed courtyards can be more appropriate than other types of courtyard. In particular,

those of semi-enclosed courtyard facing south and north of U-shape and semi-enclosed of L-shape should be preferred, regardless of the change of plot orientations, for urban housing developments where courtyard housing design is required. In other words, those of relatively higher solar gains acquired from the N-S layout have been attained mainly by the semi-enclosed courtyard types.

All the above analyses imply that lower height housing is not always an ideal option for passive solar housing in terms of obtaining solar gain through open courtyards. Similar advantage can also be provided at the scale of the higher height courtyard housing. With sensible use of housing layout planning together with reconsideration of the way the building code is applied as indicated above, solar access can be maintained even at fairly high densities. Through the careful process of selection and adaptation of a range of the strategies, urban courtyard design for solar radiation can be optimised.

7-3. Further Work

This parametric and comparative study attempts to examine the relationship between solar radiation, one of the physical influences on housing form, and urban courtyard design, and several related features. The results consist of a new methodology for analysis for solar radiation in courtyard housing design. The results could inform local authorities as well as planners and designers of the practical consequences of their use of housing layout factors, and of the implications of the use for urban passive solar housing design.

The limitations of the study and the further suggestions are summarised as below.

1. In order to suggest the beneficial effect of introducing courtyard design into urban environments, emphasis is placed on the relationship between geometrical courtyard form and solar radiation based on the housing layout factor variations. However, in addition to the courtyard form which is a decisive variable directly affecting the amount of solar gain on building facades, the inclusion of additional variables is recommended for future study. For example, writing down a range of possible independent variables for their relationships to solar radiation allows us to draw a simple expression. In other words, in addition to the geometrical consideration such as shape, proportion and orientation, these variables would consist of internal and external envelope, roof, shading devices, natural lighting quality, ventilation and heating etc, and then could be written as function of summer/winter index of performance as shown below.

Is.w = f (G, E, R, S, L ..., H)

where

Is.w: summer/ winter index of performance

G: geometrical form

E: internal/ external envelope; thermal mass

R: roof; slope and its orientation

S: shading devices; internal/ external shading on vertical/ horizontal planes

L: natural lighting quality; use of clear/ translucent/ opaque materials

H: heating; auxiliary/ ventilation

Therefore, all the independent variables need to be examined in detail for the interactions between the variables and local climatic conditions for true regional courtyard forms which bring the internal environment closer to nature.

2. Of a range of climatic parameters, the analyses have been carried out for the relative importance of the housing layout factors for the courtyard models based on solar radiation. Through this adaptation of solar radiation, it is hoped that importance of climatic responsive design will be recognised. As the understanding of the relationship between climatic parameters and housing design

needs to be further gained in depth, it is also recommendable to perceive the other thermal buffering characteristics of courtyards such as the amount of heat and light available from solar gain, and natural ventilation performance driven by wind.

3. By taking account of the realisation of energy-conscious tradition and the general preference for detached housing types, courtyard housing was chosen for the purpose of this study. On the other hand, it is also noticeable that the type of housing buildings, which provides great economy in the use of land, in Korea is in great demand because of population growth and urban concentration together with smaller size of family units in recent years. In this context, setting aside the type of the courtyard house, the scope of study on climatic responsive housing form needs to be broadening by covering various housing types for highly efficient land-utilisation, such as town house, row house and apartment buildings.

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APPENDIX 1

Lists of the Intensity of Plot Use based on Changing Housing Layout Factors

1-A. Variation in plot use based on changing the housing density factor for E-W layout with frontage to south

1-B. Variation in plot use based on changing the plot dimension factor for E-W layout with frontage to south

1-C. Variation in plot use based on changing the housing development scale factor for E-W layout with frontage to south

1-D. Variation in plot use based on changing the housing orientation factor for E-W layout with frontage to north

1-E. Variation in plot use based on changing the housing orientation factor for N-S layout

1-A. Variation in plot use based on changing the housing density factor for E-W layout with frontage to south (The Ground Area of Building: 66.89 m^2)

Table 1-A-1. 1 storey: 3.7 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	202.53	284.42	0.712	0.235	0.235
35 units/hectare	155.15	237.04	0.655	0.282	0.282
40 units/hectare	119.36	201.25	0.593	0.332	0.332
45 units/hectare	91.53	173.42	0.528	0.386	0.386
50 units/hectare	69.26	151.15	0.458	0.443	0.443

Table 1-A-2. 2 storey: 6.4 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	187.53	284.42	0.659	0.235	0.47
35 units/hectare	140.15	237.04	0.591	0.282	0.94
40 units/hectare	104.36	201.25	0.519	0.332	0.664
45 units/hectare	76.53	173.42	0.441	0.386	0.772
50 units/hectare	54.26	151.15	0.359	0.443	0.886

Table 1-A-3. 3 storey: 9.1 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	140.88	284.42	0.495	0.235	0.705
35 units/hectare	93.5	237.04	0.394	0.282	0.846
40 units/hectare	57.71	201.25	0.287	0.332	0.996
45 units/hectare	29.88	173.42	0.172	0.386	1.158
50 units/hectare	7.61	151.15	0.05	0.443	1.329

1-B. Variation in plot use based on changing the plot dimension factor for E-W layout with frontage to south (The Ground Area of Building: 66.89 m^2)

Table 1-B-1. 1 storey: 3.7 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
5 m	156.86	228.75	0.686	0.292	0.292
10 m	138.11	215	0.642	0.311	0.311
15 m	119.36	201.25	0.593	0.332	0.332
20 m	100.61	187.5	0.537	0.357	0.357
25 m	81.86	173.75	0.471	0.385	0.385

Table 1-B-2. 2 storey: 6.4 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
5 m	151.86	228.75	0.664	0.292	0.584
10 m	128.11	215	0.596	0.311	0.622
15 m	104.36	201.25	0.519	0.332	0.664
20 m	80.61	187.5	0.43	0.357	0.714
25 m	56.86	173.75	0.327	0.385	0.77

Table 1-B-3. 3 storey: 9.1 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
5 m	136.31	228.75	0.596	0.292	0.876
10 m	97.01	215	0.451	0.311	0.933
15 m	57.71	201.25	0.287	0.332	0.996
20 m	18.41	187.5	0.098	0.357	1.071
25 m	-20.89	173.75	-	0.385	1.155

1-C. Variation in plot use based on changing the housing development scale factor for E-W layout with frontage to south (The Ground Area of Building: 66.89 m^2)

Table 1-C-1. 1 storey: 3.7 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
50 units	117.86	199.75	0.59	0.335	0.335
100 units	117.86	199.75	0.59	0.335	0.335
500 units	119.36	201.25	0.593	0.332	0.332
1000 units	119.36	201.25	0.593	0.332	0.332
1500 units	118.86	200.75	0.592	0.333	0.333

Table 1-C-2. 2 storey: 6.4 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
50 units	102.86	199.75	0.515	0.335	0.67
100 units	102.86	199.75	0.515	0.335	0.67
500 units	104.36	201.25	0.519	0.332	0.664
1000 units	104.36	201.25	0.519	0.332	0.664
1500 units	103.86	200.75	0.517	0.333	0.666

Table 1-C-3. 3 storey: 9.1 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
50 units	56.21	199.75	0.281	0.335	1.005
100 units	56.21	199.75	0.281	0.335	1.005
500 units	57.71	201.25	0.287	0.332	0.996
1000 units	57.71	201.25	0.287	0.332	0.996
1500 units	57.21	200.75	0.285	0.333	0.999

1-D. Variation in plot use based on changing the housing orientation factor for E-W layout with frontage to north (The Ground Area of Building: 66.89 m^2)

Table 1-D-1. 1 storey: 3.7 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	217.53	284.42	0.765	0.235	0.235
35 units/hectare	170.15	237.04	0.718	0.282	0.282
40 units/hectare	134.36	201.25	0.668	0.332	0.332
45 units/hectare	106.53	173.42	0.614	0.386	0.386
50 units/hectare	84.26	151.15	0.557	0.443	0.443

Table 1-D-2. 2 storey: 6.4 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	217.53	284.42	0.765	0.235	0.47
35 units/hectare	170.15	237.04	0.718	0.282	0.94
40 units/hectare	134.36	201.25	0.668	0.332	0.664
45 units/hectare	106.53	173.42	0.614	0.386	0.772
50 units/hectare	84.26	151.15	0.557	0.443	0.886

Table 1-D-3. 3 storey: 9.1 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	209.13	284.42	0.735	0.235	0.705
35 units/hectare	161.75	237.04	0.682	0.282	0.846
40 units/hectare	125.96	201.25	0.626	0.332	0.996
45 units/hectare	98.13	173.42	0.566	0.386	1.158
50 units/hectare	75.86	151.15	0.502	0.443	1.329

1-E. Variation in plot use based on changing the housing orientation factor for N-S layout (The Ground Area of Building: 66.89 m^2)

Table 1-E-1. 1 storey: 3.7 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	198.57	284.42	0.698	0.235	0.235
35 units/hectare	154.35	237.04	0.651	0.282	0.282
40 units/hectare	120.94	201.25	0.601	0.332	0.332
45 units/hectare	94.97	173.42	0.548	0.386	0.386
50 units/hectare	74.18	151.15	0.491	0.443	0.443

Table 1-E-2. 2 storey: 6.4 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	179.61	284.42	0.631	0.235	0.47
35 units/hectare	138.55	237.04	0.585	0.282	0.94
40 units/hectare	107.52	201.25	0.534	0.332	0.664
45 units/hectare	83.41	173.42	0.481	0.386	0.772
50 units/hectare	64.1	151.15	0.424	0.443	0.886

Table 1-E-3. 3 storey: 9.1 m

	Net Courtyard Area (Ac), m^2	Net Plot Area (Ap), m^2	Courtyard Area Ratio (CAR)	Building Coverage (BC)	Floor Area Ratio (FAR)
30 units/hectare	125.41	284.42	0.441	0.235	0.705
35 units/hectare	92.4	237.04	0.390	0.282	0.846
40 units/hectare	67.45	201.25	0.335	0.332	0.996
45 units/hectare	48.08	173.42	0.277	0.386	1.158
50 units/hectare	32.54	151.15	0.215	0.443	1.329

APPENDIX 2

Lists of the Suitability of Courtyard Dimensions according to the Different Generic Courtyard Types

2-A. Variation in the suitability of courtyard dimensions based on changing housing density for E-W layout with frontage to south

2-B. Variation in the suitability of courtyard dimensions based on changing plot dimension for E-W layout with frontage to south

2-C. Variation in the suitability of courtyard dimensions based on changing housing development scale for E-W layout with frontage to south

2-D. Variation in the suitability of courtyard dimensions based on changing housing orientation for E-W layout with frontage to north

2-E. Variation in the suitability of courtyard dimensions based on changing housing orientation for N-S layout

Table 2-A-1. Relationship between the courtyard dimensions and the generic courtyard types: Housing Density: E-W street layout with frontage to south: 1 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
30 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)			•	•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
45 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
50 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-A-2. Relationship between the courtyard dimensions and the generic courtyard types: Housing Density: E-W street layout with frontage to south: 2 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
30 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
40 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
45 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
50 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-A-3. Relationship between the courtyard dimensions and the generic courtyard types: Housing Density: E-W street layout with frontage to south: 3 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
30 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
35 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
40 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
45 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
50 units/hectare				
Semi-enclosed I (facing south & north)		•	•	
Semi-enclosed I (facing east &west)		•	•	
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-B-1. Relationship between the courtyard dimensions and the generic courtyard types: Plot Dimension: E-W street layout with frontage to south: 1 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

5 m				
	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)				
Attached (east-west)	•	•	•	
Linear (south-north)				
Linear (east-north)	•	•	•	
10 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				
Linear (east-north)	•	•		
15 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
20 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•		
Attached (south-north)			•	•
Attached (east-west)	•			
Linear (south-north)			•	•
Linear (east-north)				
25 m				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•		
Attached (south-north)			•	•
Attached (east-west)	•			
Linear (south-north)			•	•
Linear (east-north)				

(• Suitability)

Table 2-B-2. Relationship between the courtyard dimensions and the generic courtyard types: Plot Dimension: E-W street layout with frontage to south: 2 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
5 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)				
Attached (east-west)	•	•	•	
Linear (south-north)				
Linear (east-north)	•	•	•	
10 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				
Linear (east-north)	•	•		
15 m				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
20 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•		
Attached (south-north)			•	•
Attached (east-west)	•			
Linear (south-north)			•	•
Linear (east-north)				
25 m				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•		
Attached (south-north)			•	•
Attached (east-west)	•			
Linear (south-north)			•	•
Linear (east-north)				

(• Suitability)

Table 2-B-3. Relationship between the courtyard dimensions and the generic courtyard types: Plot Dimension: E-W street layout with frontage to south: 3 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

5 m	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)				
Attached (east-west)	•	•	•	
Linear (south-north)				
Linear (east-north)	•	•	•	
10 m				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•	•		
15 m				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
20 m				
Semi-enclosed I (facing south & north)		•	•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)				
25 m				
Semi-enclosed I (facing south & north)	-	-	-	-
Semi-enclosed I (facing east &west)	-	-	-	-
Semi-enclosed II	-	-	-	-
Attached (south-north)	-	-	-	-
Attached (east-west)	-	-	-	-
Linear (south-north)	-	-	-	-
Linear (east-north)	-	-	-	-

(• Suitability)

Table 2-C-1. Relationship between the courtyard dimensions and the generic courtyard types: Housing Development Scale: E-W street layout with frontage to south: 1 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

50 units				
	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
100 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1000 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-C-2. Relationship between the courtyard dimensions and the generic courtyard types: Housing Development Scale: E-W street layout with frontage to south: 2 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
50 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
100 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1000 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				
Attached (east-west)	•			
Linear (south-north)				
Linear (east-north)	•			

(• Suitability)

Table 2-C-3. Relationship between the courtyard dimensions and the generic courtyard types: Housing Development Scale: E-W street layout with frontage to south: 3 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

50 units	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
100 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1000 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
1500 units				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)		•		
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-D-1. Relationship between the courtyard dimensions and the generic courtyard types: Housing Orientation: E-W street layout with frontage to north: 1 & 2 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

30 units/hectare	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)			•	•
Attached (east-west)	•	•		
Linear (south-north)				
Linear (east-north)	•			
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
45 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
50 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-D-2. Relationship between the courtyard dimensions and the generic courtyard types: Housing Orientation: E-W street layout with frontage to north: 3 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

30 units/hectare	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II				
Attached (south-north)			•	•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)				•
Attached (east-west)	•	•		
Linear (south-north)				•
Linear (east-north)	•			
45 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			
50 units/hectare				
Semi-enclosed I (facing south & north)			•	
Semi-enclosed I (facing east &west)				
Semi-enclosed II		•	•	
Attached (south-north)				•
Attached (east-west)	•			
Linear (south-north)				•
Linear (east-north)	•			

(• Suitability)

Table 2-E-1. Relationship between the courtyard dimensions and the generic courtyard types: Housing Orientation: N-S street layout: 1 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

30 units/hectare	Type I	Type II	Type III	Type IV
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
45 units/hectare				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•
50 units/hectare				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•

(• Suitability)

Table 2-E-2. Relationship between the courtyard dimensions and the generic courtyard types: Housing Orientation: N-S street layout: 2 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
30 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
45 units/hectare				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•
50 units/hectare				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•

(• Suitability)

Table 2-E-3. Relationship between the courtyard dimensions and the generic courtyard types: Housing Orientation: N-S street layout: 3 storey
(Minimum building depth assumed 1.8m based on 30cm grid module)

	Type I	Type II	Type III	Type IV
30 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
35 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
40 units/hectare				
Semi-enclosed I (facing south & north)				
Semi-enclosed I (facing east &west)				
Semi-enclosed II			•	
Attached (south-north)	•	•		
Attached (east-west)				•
Linear (south-north)	•	•		
Linear (east-north)				•
45 units/hectare				
Semi-enclosed I (facing south & north)		•		
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•
50 units/hectare				
Semi-enclosed I (facing south & north)		•	•	
Semi-enclosed I (facing east &west)			•	
Semi-enclosed II		•	•	
Attached (south-north)	•			
Attached (east-west)				•
Linear (south-north)	•			
Linear (east-north)				•

(• Suitability)

APPENDIX 3

Shadowpack – P.C.

Version 2.0

(Case Study of a Simple Model)

3-A. Model data structure

A three dimensional model (or an element of a model) is specified by a list of vertices, a list of lines, and a list of polygonal planar faces define the outer boundaries of the solid objects.

Vertices are specified by a vertex number (simply the order in the list) followed by the three (x,y,z) coordinates. Lines are specified by pairs of vertex numbers.

Planar faces are specified by three or more vertices going around the polygonal boundary in a clockwise direction when viewing it from the outside.

A face can have any number of polygonal holes in it. These holes are also specified by the appropriate vertices, again going around clockwise when viewed from the outside of the face. Holes are therefore specified in the same way as faces and always follow immediately the containing face in the list of faces.

A record in the list of faces has the following form:
IP, N, NH, V1, V2, V3 ..... VN

Where:
IP = the face number (its order in the list)
N = the number of vertices in the outer boundary of the plane, (maximum = 16)
NH = the number of holes in the plane
V1 .... VN = the vertex numbers of the outer boundary

If NH is a positive (non-zero) integer the specifications of the NH holes will follow in the next NH records. The convention is adopted that if NH = -1 the object represented in the record is a hole.

In addition to the geometrical specification described above each new element which is created is classified as an "object" which can have "attributes". At present the only attribute which can be given is a number which can be used to define the colour of the object for visualisation purposes, but in principle other attributes can be added. The list of objects follows the list of planes in the data structure. Objects are numbered in increasing order, and each object is specified by the sequence of bounding planes which comprise it. An object can also be a single plane, for example the ground plane. A record in the list of objects has the following format:

IO, NP1, NPL, IA1

Where:

IO = the object number (its order in the list)

NP1 = the first bounding plane of the object

NPL = the last bounding plane of the object

IA1 = the first (and presently only) attribute of the object, its colour.

An example of a simple cube standing on a ground plane is given below.

Example Cube Model

The following gives the lists of vertices, lines and faces for the simple model of a cube (dimensions 10 x 10 x 10 m) standing on a ground plane (dimensions 50 x 50 m).

Vertices: 12

1	-25.000	.000	–25.000
2	25.000	.000	-25.000
3	25.000	.000	25.000
4	-25.000	.000	25.000
5	-5.000	.000	-5.000
6	5.000	.000	-5.000
7	5.000	.000	5.000
8	-5.000	.000	5.000
9	-5.000	10.000	-5.000
10	5.000	10.000	-5.000
11	5.000	10.000	5.000
12	-5.000	10.000	5.000

Lines: 16

1	2
2	3
3	4
4	1
5	6
6	7
7	8
8	5
9	10
10	11
11	12
12	9
5	9
6	10
7	11
8	12

Planes: 7

1 4 0 1 2 3 4

2 4 0 8 7 6 5

3 4 0 9 10 11 12

4 4 0 5 6 10 9

5 4 0 6 7 11 10

6 4 0 7 8 12 11

7 4 0 8 5 9 12

Objects: 2

1 1 1 1

2 2 7 1

3-B. Example set of results

The following set of results were obtained using the program SHADEN with the model of the cube on a ground plane. The control parameters were those given in the example file cube.cnt.

clear

ROT = .00 LAT = 37.34 NPI = 4 ITRY = 0 XSI YSI = 1.00 1.00

PLANE	AREA	AZN	ELN
Ground Plane: 1	2500.00	.0	90.0
Cube plane facing east: 5	100.00	-90.0	.0
Cube plane facing south: 6	100.00	.0	.0
Cube plane facing west: 7	100.00	90.0	.0

MONTH 1

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	308.5	263.4	771204.3	658407.7	.854
5	170.6	170.6	17060.9	17060.9	1.000
6	589.3	589.3	58927.3	58927.3	1.000
7	170.6	170.6	17060.9	17060.9	1.000
SUM OF ENERGIES RECEIVED			864253.4	751456.8	.869

MONTH 2

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	386.0	337.0	965087.3	842529.4	.873
5	202.9	202.9	20293.8	20293.8	1.000
6	529.8	529.8	52982.3	52982.3	1.000
7	202.9	202.9	20293.8	20293.8	1.000
SUM OF ENERGIES RECEIVED			1058657.0	936099.4	.884

MONTH 3

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	572.7	511.2	1431850.0	1278050.0	.893
5	281.3	281.3	28128.8	28128.8	1.000
6	501.9	501.9	50185.7	50185.7	1.000
7	281.3	281.3	28128.8	28128.8	1.000
SUM OF ENERGIES RECEIVED			1538293.0	1384493.0	.900

MONTH 4

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	690.8	628.6	1726977.0	1571467.0	.910
5	311.7	311.7	31165.3	31165.3	1.000
6	317.5	317.5	31753.2	31753.2	1.000
7	311.7	311.7	31165.3	31165.3	1.000
SUM OF ENERGIES RECEIVED			1821061.0	1665551.0	.915

MONTH 5

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	799.7	734.8	1999134.0	1836905.0	.919
5	337.1	337.1	33714.6	33714.6	1.000
6	186.9	186.9	18685.1	18685.1	1.000
7	337.1	337.1	33714.6	33714.6	1.000
SUM OF ENERGIES RECEIVED			2085248.0	1923019.0	.922

MONTH 6

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	803.9	741.2	2009874.0	1853016.0	.922
5	327.0	327.0	32701.0	32701.0	1.000
6	120.1	120.1	12010.8	12010.8	1.000
7	327.0	327.0	32700.9	32700.9	1.000
SUM OF ENERGIES RECEIVED			2087287.0	1930429.0	.925

MONTH 7

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	807.5	743.7	2018806.0	1859150.0	.921
5	330.9	330.9	33086.4	33086.4	1.000
6	144.4	144.4	14435.3	14435.3	1.000
7	330.9	330.9	33086.4	33086.4	1.000
SUM OF ENERGIES RECEIVED			2099414.0	1939758.0	.924

MONTH 8

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	730.6	668.8	1826520.0	1671905.0	.915
5	313.8	313.8	31375.8	31375.8	1.000
6	247.1	247.1	24714.4	24714.4	1.000
7	313.8	313.8	31375.8	31375.8	1.000
SUM OF ENERGIES RECEIVED			1913986.0	1759371.0	.919

MONTH 9

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	590.3	532.0	1475687.0	1330106.0	.901
5	273.9	273.9	27391.5	27391.5	1.000
6	397.9	397.9	39788.5	39788.5	1.000
7	273.9	273.9	27391.5	27391.5	1.000
SUM OF ENERGIES RECEIVED			1570259.0	1424678.0	.907

MONTH 10

PLANE	---MJ/M.SQ--- UNSHADED	SHADED	----MJ---- UNSHADED	SHADED	RATIO
1	464.1	409.1	1160287.0	1022800.0	.882
5	233.3	233.3	23332.3	23332.3	1.000
6	536.9	536.9	53693.1	53693.1	1.000
7	233.3	233.3	23332.3	23332.3	1.000
SUM OF ENERGIES RECEIVED			1260645.0	1123158.0	.891

MONTH 11

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	322.6	277.3	806524.8	693297.1	.860
5	173.6	173.6	17364.4	17364.4	1.000
6	557.1	557.1	55707.4	55707.4	1.000
7	173.6	173.6	17364.4	17364.4	1.000
SUM OF ENERGIES RECEIVED			896960.9	783733.3	.874

MONTH 12

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	277.3	235.7	693131.8	589194.0	.850
5	155.1	155.1	15509.2	15509.2	1.000
6	576.7	576.7	57669.1	57669.1	1.000
7	155.1	155.1	15509.2	15509.2	1.000
SUM OF ENERGIES RECEIVED			781819.3	677881.5	.867

YEARLY TOTALS

	---MJ/M.SQ---		----MJ----		
PLANE	UNSHADED	SHADED	UNSHADED	SHADED	RATIO
1	6754.0	6082.7	16885080.0	15206830.0	.901
5	3111.2	3111.2	311123.9	311123.9	1.000
6	4705.5	4705.5	470552.3	470552.3	1.000
7	3111.2	3111.2	311123.9	311123.9	1.000

ANNUAL TOTAL FOR ALL FACES (MJ/M.SQ)*AREA

UNSHADED	SHADED	RATIO
17977880.0	16299630.0	.907

3-C. Clear skies radiation formula

The correction for variation in earth-sun distance, Cr, is calculated using the formula:

$$Cr = 1.0 + 0.033 * COS(2.0 * \pi * IDAY / 365.24)$$

Where IDAY is the day number.

The intensity of direct radiation received at the surface of the earth is then given by:

$$I = 1.37 * Cr * 0.87 * EXP(-A / SIN(EL)) \quad \text{kw/sq.m.}$$

Where EL = the elevation of the sun,

And A = the atmospheric extinction coefficient.
Values for A taken from the ASHRAE "Algorithms for building heat transfer subrouthines", valid for the 21st of the month are:

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142

by simple interpolation we find values for the 7th of the month:

0.142	0.143	0.150	0.168	0.188	0.200	0.206	0.204	0.189	0.168	0.155	0.145

From the first to the 15th of the month the lower row of figures is used, while from the 16th to the end of the month the upper row is used (by both programs SHADEN and ISOSUN).

3-D. TRY data fomat

Test Reference Year Data is read in a format corresponding to that provided by the Thermal Insulation Laboratory of the Technical University of Denmark.

Each record contains one hours data, with station name, year, month, day hour etc. as follows:

Station Name (abbr)
Time indicator T (ST) or L (Local)
Dry bulb temp. (tenths of deg.C)
Global Radn. Horiz. Surf. (Joules/cm.sq.)
Diff. Normal Radn. (Joules/cm.sq.)
Direct Radn. (Joules/cm.sq.)
Sunshine Duration (minutes)
Humidity
Wind Velocity
Indicator for artificial data
Year, Month, Day, Hour

The only data currently used by programs SHADEN and ISOSUN is the direct radiation.

The programs require a condensed form of the TRY obtained by selecting only four days per month; normally the 4^{th}, 11^{th}, 18^{th} and 25^{th}. The choice of days selected can be changed to investigate the sensitivity of the results to this.