DWELLING DENSIFICATION AND "GREENNESS":
Hong Kong's High-Density Housing And Resource Conservation

by

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ABSTRACT

Urban dwelling densities have profound implications on the form of built environment, which in turn incurs significant effects on the patterns of resource use associated with housing construction and operational needs. Hong Kong is a compact, industrialized city with housing at very high densities. This thesis proposes and tests the hypothesis that Hong Kong's housing represents a green model of residential development which is conducive to low per capita consumption. Reducing per capita consumption is a primary greening agenda, especially for industrialized regions. "Wastes" are also increasingly seen as resources. This thesis addresses three aspects of resource use: energy, water (including "wastewater"), and materials (including solid "waste").

Hong Kong's housing development is commonly in the form of estates which are characterized by large site area measured in hectares and towers of 30-40 storeys. The current densities are 2000-4000 residents per hectare of net site area, plot ratio of 5 and above, 1-2 square metres of communal open space per resident, and 15-20 square metres of gross floor area per resident. In contrast, the corresponding densities of North American single-family dwelling are 50-100 residents per hectare of net site area, plot ratio of less than 1, about 100 square metres of private open space per resident, and 80-100 square metres of floor area per resident.

The analysis offered in this thesis shows that Hong Kong's dwelling densification is conducive to efficient centralized systems such as mass transit, sea-water flushing, and inorganic waste segregation -- which consequently lead to low per capita consumption of fossil fuels and potable water and high per capita recovery of domestic solid waste. On a building level, the attached, compact dwelling configuration also leads to low per capita energy and material use associated with housing construction. However, very high "building densities" entail physical/spatial constraints on a number of greening practices, such as harnessing of ambient wind for space cooling and on-site recovery of wastewater and organic waste. A direction towards high "occupancy density" in company with moderate "building density" should be considered as a greener housing alternative in long term.
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INTRODUCTION

Environmental Conservation & Global Population

Currently, the world faces key environmental problems: global warming from greenhouse gas emissions, inadequate supply of potable water, depletion of natural resources, deforestation, and reduced capacity for food production (Brown et al., 1995; Girardet, 1992). Over-exploitation threatens the very existence of the life-supporting systems and to cause irreversible damages; it strains the limits of the Earth's "carrying capacity" -- its ability to provide the resources required to sustain life while retaining the capacity to regenerate and remain viable. All of these issues are exasperated by an exponentially increasing world population. According to Ehrlich and Ehrlich (1992) and Grant (1992), the current environmental problems are driven by three basic variables, which are a part of both the problems and the solutions:

- **POPULATION** (the population size, distribution, and other demographic characteristics),
- **AFFLUENCE** (the level of per capita consumption), and
- **TECHNOLOGY** (the measure of the impact of technologies involved in the production, consumption, and waste disposal processes).

This thesis is concerned with the relationship between urban dwelling densities and the levels of *per capita* consumption of natural resources from the viewpoint of architectural and urban design. Gottfried (1996) points out, "as the world's population continues to expand, implementation of resource-efficient measures in all areas of human activities is imperative. The built environment is one clear example of the impact of human activity on resources." (p. vii). A fundamental premise on which this study rests is that urban dwelling densification has profound influence on the form of built environment, which in turn incurs significant effects on per capita consumption of resources and consequently human impact on the carrying capacity of the planet. The issue of dwelling density is an important component in addressing the *greenness* of architecture (and city).
Green Design & "Context of Operation"

As asserted by Yeang (1995), *green architecture* or *sustainable architecture* are simply different terms for "designing with nature" and designing in an environmentally responsible way. The increasing concern over the impairment of the earth's natural systems (i.e., the ecosystems within the biosphere) has elicited a variety of reactions from "designers" resulting in many views toward ecologically responsive design. In this discussion, *designers* are interpreted as architects, engineers, environmental consultants, landscape architects, planners, urban designers, and other authorities who share key responsibilities in shaping the urban built environment. However, no matter what are the ecologically responsive design strategies and professional disciplines, the actual planning and design operations (and the eventual human impact on the environment) are inevitably subject to significant effects of local physical context: the "context of operation". The "context of operation" can be categorized into two broad aspects: (1) the local natural environment, and (2) the human environment. The local natural environment refers to site climate, topography, etc. In a city, the form of man-made environment can be described in terms of building design, layout, height, etc. -- which are in turn subject to the influence of basic design variables such as the extent of urbanization (the size of city, etc.) and the density of developments (especially "dwelling densities").

**Housing, Density & Per Capita Resource Consumption**

Dwelling is a basic human need. As pointed out by Bhatti *et al.* (1994) in *Housing and the Environment: A New Agenda*, "the provision of housing is a basic necessity that consumes a vast amount of natural resources." (p. 13). Indeed, a major component constituting the urban area of a city is its residential sector. Evans (1973) suggests in *Housing Layout and Density*, "residential areas are by far the largest single land-use in cities. Changes in net residential density thus will have great effects on gross density." (p. 7). In *Good City Form*, Lynch (1981) further states that the density of housing is always a fundamental decision in city design, and it sets the framework for all the other features and has far-reaching implications.
The emphasis of this thesis is confined to the environmental problems that are attributable to people and the built environment, and particularly the relationship between urban dwelling densification and greenness -- which is to be measured with respect to the levels of per capita consumption, i.e., "less is greener". This study assesses the implications of urban dwelling densification on the patterns of resource use associated with the construction and maintenance of housing and the recurring operational needs of dwellers. In addition to transforming land into building site, housing development consumes resources including fuels and materials, and generates wastes during the process of construction. Upon completion, the physical characteristics of built environment continue to influence the use of natural resources, such as the patterns of fuel, water and material use for the operations, maintenance and demolition of building and the daily living of the occupants. The form of physical environment exerts further implications on the treatment of liquid and solid wastes disposed of from dwelling units.

**Per Capita Resource Consumption: Less is Greener**

Environmental problems are frequently interpreted in terms of pollution and environmental degradation, and perceived to be local. In Hong Kong, for instance, the focus is still commonly placed on local issues such as noise, air, water pollution, and shortage of landfill sites. However, in the discussion of greening the city, the scope of environmental concern should be extended beyond local anti-pollution measures, with emphasis on a wider perspective including the regional and global levels. Ashworth *et al.* (1993) advocate that the term environment should be used in its totality, rather than the customary approach of viewing the environment as being simply a matter of local pollutions. Environmentalist Thilo Bode contends that the real environmental problem is the rate of resource consumption (Jackson, 1996). As further pointed out in *Our common Future* published by the United Nations World Commission on Environment and Development (WCED, 1987), the industrialized "world cities" account for a high share of the world's resource use, energy consumption, and environmental pollution; many have a global reach and draw their resources and energy from distant lands with enormous aggregate impacts on the ecosystems of those lands.
Hence, the fundamental position taken from a global perspective is that reduction on per capita consumption is a primary method of conservation in the transition to a sustainable world. Enlightened local actions are imperative, since many of these critical global issues are rooted in local, day-to-day problems. To reduce per capita consumption of natural resources and per capita generation and disposal of "wastes" becomes a key environmental conservation, or greening, agenda -- especially in the industrialized regions where some 20 percent of the world population consumes 80 percent of the world resources. If the scale of demand for resources is mismanaged, other strategies such as reuse and recycling will ultimately prove irrelevant (Cole, 1996; Girardet, 1995; Khoshsun, 1990). According to the "3R's hierarchy principle", consuming less (reduce) is the most effective means of resource conservation and waste reduction; reuse and recycling rank after reduce (GVRD, 1995; trainer/GVRD, 1996).

As pointed out by Breheny et al. (1993), there is an increasing concern that urban areas should stress the need to reduce both the urban use of natural resources inputs and the urban production of undesirable outputs of waste. In addition to per capita reduction in the exploitation of land for urban development, two broad aspects of reduction related to housing construction and occupation are hence considered in this study: (1) to reduce per capita consumption of natural resources including fossil fuels, potable water, and raw materials; and (2) to reduce per capita generation of wastes (including construction refuse, and household wastewater and solid waste), and subsequent disposal of the wastes (through increasing the ease or efficiency of waste recovery "on-site").

Density: Low or High

Density is one of the most important development control standards. A main parameter describing the form of residential settlements is its density. For the design of a new town or a housing estate, density is also the commonly used briefing target, and perhaps has a disproportionate influence on the built forms, and subsequently on the usage patterns of natural resource and the associated environmental impacts. As suggested by Hughes (1994a) in Hong Kong Architecture: A Product of Density, density is the prime generator of the built form in Hong Kong.
Low residential densities in sprawling cities as those typical in North America and Australia are increasingly criticized as a root of their high per capita environmental impact related to the over-consumption of natural resources such as land, energy, water, and raw materials. On the other hand, the environmental benefits of urban dwelling densification is advocated by increasing number of authors. Research indicates that in general higher urban and housing densities are effectively conducive to lower per capita consumption of natural resources such as arable land, fossil fuels and raw materials as well as higher level of household solid waste recovery (Elkin et al., 1991, in Bhatti et al., 1994; Engwicht, 1993; Lang, 1985; Newman and Kenworthy, 1989; Replogle, 1991; Wackernagel, 1994; Walker, 1995). Consistent with other social and economic merits of densification, increasing housing densities is hence promoted, especially in the spread cities of North America and Australia (Calthorpe, 1989a, 1989b; Chiras, 1992; Owens, 1992; Roseland, 1992; Wackernagel and Rees, 1996).

Density: Hong Kong versus Other Industrialized Cities

Hong Kong, a British colony since the 1840s and now an international financial and trading centre located on the southern coast of China, represents a classic compact city with housing at extremely high densities (Gilchriest, 1994; Kojima, 1992; Ohno, 1992; Pun, 1994). As portrayed by Marsden (1994), "closely-packed, high-rise, multi-use buildings give [Hong Kong] much of its distinctiveness ... The high density is not achieved by individual tall buildings but by overall stature." (p. 32-4). For Hong Kong's current population of some six million (approximately one-thousandth of world population), its overall urbanized area and gross residential area merely occupy about 15,000 and 6,000 hectares of land respectively as a result of the extremely high levels of densification. As described by Marsden (1994), the area of 15,000 and 6,000 hectares could be fitted into a circle with 7 and 4 kilometre radius respectively; by contrast, Chicago (a typical "spread city" with a similar population) would require a 25 kilometre radius just for its gross residential area (twice as large as the entire territory of Hong Kong). Figure 1.1 illustrates the relative size of gross residential area in Hong Kong and Chicago.
The figure illustrates the comparative size of residential areas between Hong Kong and a typical North American city (with a similar population) such as Chicago. The diagram shows:

- **Hong Kong**
- **Typical North American City**

**Figure 1.1** Comparative size of residential area between Hong Kong and typical North American city

Source: (Adapted from Marsden, 1994)
Through dwelling densification, Hong Kong has minimized urban encroachment into rural land. Hong Kong's total urbanized and gross residential areas currently account for less than 15 and 6 percent of the territory respectively, even though its territorial land area is only about 110,000 hectares. In spite of the fact that Hong Kong's sovereignty is going to be reverted to China as a Special Administrative Region by mid-1997, the territorial boundary will remain and as will its high densities.

Urban dwelling densification is a key underlying factor contributing to the compact city form of Hong Kong, and continues to be a central issue in the planning and architectural design. Amongst the industrialized world cities, Hong Kong has a unique urban form, especially of its housing sector. Kojima (1992) describes, "there is no suburban sprawl in Hong Kong". (p. 66). In Hong Kong, the majority of the population dwell in multi-family buildings of twenty storeys and above, and relatively tight interior space standards are the norm.

By contrast, urban sprays are common in the urbanization process of Western countries. Chiras (1992) contends, "the modern city and suburb are the product of [perceived] abundance. Cheap oil and ample supplies of timber and other natural resources have permitted this unwieldy form of human habitation to evolve and thrive, if only for a while." (p.182). Figure 1.2 compares the typical dwelling densities (in terms of "occupancy density", "building density", and "residential density") between Hong Kong and other industrialized world cities. Hong Kong's dwelling densities are remarkably higher than those in the North American, Western European and other developed Asian cities (such as Tokyo and Singapore).

**Density: A Multivalent Concept**

Dwelling densities can be described and measured in different ways, depending on the purpose of measurement. This thesis is primarily concerned with "occupancy density", "building density", and "residential density". The definitions of density vary between researchers. In this study, the definitions of dwelling density are as follows (see also the definitions of density in Chapter I):
FIGURE 1.2 COMPARATIVE DWELLING DENSITIES BETWEEN HONG KONG AND OTHER INDUSTRIALIZED WORLD CITIES
Source: (Adapted from Hughes, 1995a; Marsden 1994; Pryor and Pau, 1993a)
• "Occupancy density" is defined as the ratio between the amount of construction floor area (or gross floor area) and the number of occupants. A higher occupancy density means less floor space per occupant.

• "Building density" refers to the relationships between the size (or volume) of buildings and their development site. The primary unit of measuring building density is in term of plot ratio (or floor space ratio). A higher building density means more floor space developed per unit of development land area.

• "Residential density" measures the number of residential population per unit of area of development land. A higher residential density means more people accommodated per unit of land area.

Figure 1.2 further illustrates that increasing residential densities have a close correlation with increasing occupancy densities and building densities. For instance, the typical occupancy density, building density, and residential density in the spread cities in North America and Australia are about one-fifth, one-tenth and one-fiftieth respectively of those in Hong Kong. Theoretically, however, occupancy density and building density are independent from each other, i.e., a high occupancy density is not necessarily associated with a high building density, or vice versa.

A Case Study: Hong Kong’s High-Density Housing & Per Capita Resource Consumption

Urban dwelling densification is evidently conducive to lower per capita consumption of land for housing and the associated infrastructures through an increased use of vertical space and improved efficiency of scale and proximity (D'amour, 1991, in Shawkat, 1995; Pun, 1994; Tjallingii, 1995). According to Marsden (1994),

"evidence scattered throughout the international literature suggest a working hypothesis that for large cities, at similar stages of economic development ... infrastructural efficiency peaks at around 175-225 persons per hectare [urban density, or 350-450 persons per hectare gross residential]." (p. 39).
While Hong Kong evidently has high land-use and infrastructural efficiencies from the above perspective, this thesis concentrates on assessing the implications of its high-density housing on the usage pattern of three key resources related to various housing construction stages and daily operations (see also Figure 1.3):

- **ENERGY**
  
  The categories of energy use associated with housing construction include initial and recurring embodied energy, and demolition energy, whereas the energy use for daily operations can be distinguished into operating energy and commuting energy. (See Chapter II for the definition of embodied energy, operating energy, commuting energy, etc.);

- **WATER**
  
  Domestic water use is distinguished into potable use, toilet flushing, and landscape irrigation. On the other hand, household "waste" water and rainwater are potentially resources, which are commonly under-utilized (especially in cities) and can be beneficially used on-site.

- **MATERIALS**
  
  Materials are consumed for initial construction and recurring maintenance of buildings, whereas solid "waste" materials are generated at various building stages, including demolition. On the other hand, household solid waste, comprising both organic and inorganic constituents, represents another significant waste stream in the urban area; the reduction of waste (which would otherwise be destined for disposal) through the recovery of recyclable/compostable materials is a key concern.

If increasing housing density is a design variable that is effective in reducing per capita environmental impact, is Hong Kong's prevalent form of high-density housing a relatively *green* model -- given that the measurement of *greenness* is evaluated with respect to the levels of per capita consumption of these three kinds of resource? Moreover, what are the characteristics of housing design that foster such effects? The study of Hong Kong's experience in densification may potentially offer lessons to designers in the search for a *green* design of the built environment.
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FIGURE 1.3 RESOURCE USE ASSOCIATED WITH HOUSING PROVISION AND DAILY/DOMESTIC OPERATIONS
CHAPTER I

DWELLING DENSIFICATION

1.1 THESIS OBJECTIVES & ORGANIZATION

1.1.1 Purpose & Objectives

The primary purpose of this thesis is to estimate the influence of Hong Kong's dwelling densification on the consumption pattern of natural resources, including energy, water and materials, on a per person (per capita) basis. The levels of per capita consumption of natural resources are used as indicators of greenness. Hong Kong is taken as a study case which represents a compact, industrialized "world city" with housing at very high densities. Hong Kong's high-density housing is contrasted with low-density residential development in other industrialized cities (especially, the spread cities in Canada and the United States, such as Vancouver, B.C.), in order to highlight the physical/spatial characteristics of dwelling densification that influence the per capita consumption patterns.

The hypothesis is that Hong Kong's prevalent form of high-density housing is conducive to low levels of per capita consumption of natural resources. The specific objectives are:

- FRAMEWORK OF ASSESSMENT
  
  To develop a framework for assessing the relationship between dwelling densities and per capita consumption pattern of resources including energy, water, and materials;

- OPPORTUNITIES & CONSTRAINTS
  
  To identify the key opportunities and constraints of Hong Kong's dwelling densification with respect to the reduction of per capita consumption of natural resources;

- "GREEN" HOUSING DESIGN
  
  To explore the implications for "green" housing design, particularly with respect to the levels and aspects of dwelling densification and the design strategies for housing at high densities.
1.1.2 Thesis Organization

The thesis is organized in six chapters. Chapter One introduces the thesis hypothesis, objectives and organization; the definitions of density and the related concepts (such as high-rise versus high density); and the backgrounds and physical characteristics of dwelling densification in Hong Kong, including the current archetype of high-density dwelling.

Chapter Two introduces a framework for analyzing the relationship between the "indicators of dwelling densification" (including occupancy density, building density, and residential density) and the "indicators of greenness" (referring to three main categories of resource consumption: energy, water, and material use). The key components (or sub-categories) of these three categories of resource use are then examined for the formation of an assessment matrix. In addition, the detail of assessment is discussed with respect to the method of research (e.g., quantitative versus qualitative analysis), and the selection of a dwelling model for comparison (in this case, the detached single-family house -- dwelling archetype in the suburbs of North American cities).

Chapters Three, Four, and Five examine the selected elements of resource use: energy, water, and material respectively. Within each of these chapters, there are two main concerns: (1) to evaluate the states of resource use related to the dwelling archetype in Hong Kong and North American cities, and (2) to examine the efficiency (and inefficiency) of resource use achievable through the process of dwelling densification as that prevalent in Hong Kong. The discussion also covers the key underlying physical/spatial parameters that contribute to (or constrain) the efficiency of resource use in Hong Kong's high-density housing development, and connects them with the associated key environmental impacts in need of attention.

Chapter Six concludes the research findings with a discussion on the directions for green housing development and the recommendations for further research.

The appendices contain abbreviations and a glossary of terms commonly used in the building industries of Hong Kong as well as other specific terms used in this thesis.
1.2 DEFINITIONS OF DENSITY

1.2.1 Overview

Although the environmental merits of dwelling densification are increasingly advocated by practitioner and academic (e.g., Hughes, 1994b; Thom et al., 1994), the interpretation of density(s) often varies considerably according to each author. Clear definitions and boundaries are thus essential parts of discussion accompanying the analysis of dwelling densification. Fouchier (1994) suggests, "there is in fact not one single density, but a multitude of densities which can be analyzed, according to the referred geographical area ... Density only takes on a real meaning if it is related to a scale of reference". (p. 8).

While Hong Kong is often described as one of the most dense cities in term of its territorial density (currently about 60 persons per hectare), such description do not convey an accurate picture of densification in this city. To illustrate a more comprehensive scenario, Table 1.1 presents the population densities with respect to the different "scales of reference" in Hong Kong. The population densities are distinguished into five types in a descending order of geographic/physical scales:

- TERRITORIAL DENSITY,
- URBAN DENSITY,
- GROSS RESIDENTIAL AREA DENSITY,
- NET RESIDENTIAL DENSITY,
- OCCUPANCY DENSITY.

Theoretically, density means a ratio between a quantity or a statistical indicator (population, number of households, square metres of floor surface or open space, etc.) and the occupied surface or three-dimensional space (gross or net surface of land, or other indicators of space at different geographical levels) (Fouchier, 1994; Hughes, 1995a; Walker, 1995). In addition to population density, building density (or structural density) is another key concern in this thesis. Table 1.1 also includes the measurement of building density, in terms of plot ratio (PR) and open space ratio.
<table>
<thead>
<tr>
<th>POPULATION DENSITY</th>
<th>SCALE OF REFERENCE (Land Area and Percentage of Territory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Territory</td>
<td>Urbanized Area</td>
</tr>
<tr>
<td>110,000 hectares (100%)</td>
<td>15,000 hectares (about 13 to 14%)</td>
</tr>
<tr>
<td>POPULATION DENSITY</td>
<td>Territorial Density</td>
</tr>
<tr>
<td>about 60 persons per hectare land area</td>
<td>varied: 300 to 600 persons per ha land area</td>
</tr>
<tr>
<td>BUILDING DENSITY</td>
<td>Floor Space Ratio: about 5 to 10 plot ratio</td>
</tr>
<tr>
<td></td>
<td>Open Space Ratio: about 1 to 2 m² per person</td>
</tr>
</tbody>
</table>

Source: (Hughes, 1995a, 1995b; Marsden, 1994; Pryor and Pau, 1993b)
In addition to illustrate the current levels of dwelling densification prevalent in Hong Kong, this section defines the various relevant terms used in the description and definition of density. The average density of resident population in the main urbanized areas of Hong Kong, i.e., urban density, is first introduced. As this thesis focuses on the scale of individual residential estates, the population density of a residential estate (or commonly called residential density) has to be further clarified in terms of gross and net measurements. It is necessary to differentiate between net residential density and the resident population density of gross residential area, the latter being interpreted on a larger geographical scale. On the one hand, the interrelationships among urban density, gross residential area density and net residential density, and their implications on urban and building forms are introduced. On the other, the close interrelationships among residential density, occupancy density, and building density are discussed, with the definitions of occupancy density and building density presented in the subsequent sub-sections. The basic unit in the measurement of residential floorspace is defined in term of gross floor area.

While Hong Kong is characterized by both high densities and widespread development of high-rise housing, high densities do not necessarily imply high-rises, or vice versa. It is therefore useful to clarify the concept of high-rise, and explains the interrelationships between high-rise development and high densities in the residential context of Hong Kong.

1.2.2 Urban Density

Density in the urban development context can be calculated for the concentration of people, jobs, building structures, or dwellings per unit area of urbanized land. In this thesis, the measurement of urban density is based on resident population per unit of urbanized land. The urban density in Hong Kong is currently represented in the order of 300 to 400 persons per hectare on average. By contrast, the urban densities of spread cities in Europe/North America are typically in the order of about 50 and 25 persons per hectare respectively (Hughes, 1994b, 1995a; Newman and Kenworthy, 1989).
The majority of Hong Kong's population reside in two main categories of urban area: (1) Metro area (i.e., the more highly urbanized areas in Hong Kong Island and Kowloon Peninsula around Victoria Harbour, as opposed to the new towns developed in the New Territories), and (2) new towns. The current urban density in the Metro area and new towns is approximately 600 and 300 persons per hectare respectively. Such densities over much of the main urbanized area, however, are gradually decreasing as household sizes fall and sharing of flats decreases (Marsden, 1994).

1.2.3 Residential Densities

According to Marsden (1994), there is a distinct relationship between urban density, and gross and net residential densities: the urban density is approximately twice the population density of gross residential area, and the gross residential area density is approximately twice the net residential density. In Hong Kong, on the scale of its whole territory, the current urban density, gross residential area density, and net residential density are approximately 350, 1,000, and 2,500 persons per hectare respectively (see Table 1.1). Therefore, theoretically, halving the current average net density of residential area would roughly double the gross residential area, and lead to about 50 percent increase in the total size of the urbanized area. In other words, the existing urbanized area in Hong Kong would be expanded from approximately one-seventh to one-fifth of the territory. Another halving of the current density of residential area would further lead to urban sprawling over one-third of the total land area in Hong Kong. These conjectures indicate that the effects of dwelling densification (or dwelling de-densification) on the city form is profound, especially in view of Hong Kong's small territory.

Despite the significant implications of residential area, the concept of density is "elusive" as described by Gaitanakis (1995). There are a variety of indicators of dwelling densification; the appropriate way to use an indicator (or a combination of indicators) depends on the purpose of assessment and the context of measurement. An assessment of densification can be conducted on different scale(s) of reference: a household unit, residential estate, or residential district.
The gross and net measurements should also be clearly distinguished wherever appropriate. On the scale of individual residential estates, if residential density is defined as the number of resident population per unit area of land, the ambiguity lies on the definition of land area. For a site of residential estate development in Hong Kong, the gross land (or site) area commonly refers to the overall size of the lot whereas the calculation of net land area usually excludes internal road space and sometimes other non-developable areas such as steep slopes. Therefore, gross residential density is measured in term of persons per gross site area, while net residential density is calculated on the basis of net site area. In a high-density residential development, the road space usually takes up about 10 to 20 percent of the site area. In practice, the difference between gross and net site areas mainly depends on the specific characteristics of a development site (e.g., its shape, size, topography and the surroundings) as well as the other planning and design parameters.

The focus of this study is directed on the net residential density of individual residential estates, since it leads to more direct implications on building design and in turn the pattern of resource use. The net residential densities in the development of housing estates in Hong Kong typically range from 2,000 to 4,000 persons per hectare of land area. The average is approximately 2,500 persons per hectare. Nevertheless, the densities are extremely high, especially as compared with the corresponding densities in the typical sprawling suburbs in North America (which are in the order of 50 persons per hectare). According to Hughes (1995a), the net residential density of a residential estate is closely related with occupancy density and building density. Quantitatively, the interrelationship among net residential density, occupancy density and building density can be represented in the following relationship:

"Net Residential Density = Occupancy Rate \times Building Density ".

According to this relationship, higher residential densities is achievable through increasing occupancy densities and/or increasing building densities. In Hong Kong, the high residential density is currently characterized by its both high occupancy density and high building density.
1.2.4 Occupancy Density

Occupancy density is inversely proportional to occupancy rate. The latter is measured in term of the average amount of floorspace available per resident. While representing a measurement of internal density in homes, occupancy density is a key factor influencing the densities of population at the upper scales of reference. For instance, without varying the building density, halving the occupancy rate would almost mean halving the net residential density, and in turn the effects on the gross residential area density and urban density would be profound as well.

In this study, occupancy density is interpreted on the basis of gross floor area, instead of net or internal floor area sometimes used in other studies. Such preference is based on the fact that gross floor area is the most widely used indicator of home size in Hong Kong, and it is most closely linked with the actual construction floor area -- which is a primary index for measuring the consumption of building materials and energy. In Hong Kong, gross floor area is commonly defined as the total floor area enclosed within the outer surface of external walls. In the case of apartment buildings, common areas such as lobbies, lift shafts, and escape stairs, are also included in the calculation of gross floor area and each dwelling unit has a proportionate share of the common areas. The usable floorspace inside an apartment unit is hence smaller than its gross floor area. In general, the usable floorspace of an apartment unit represents about 80 percent of its gross floor area after exclusion of the floorspace occupied by external walls and common areas.

The typical occupancy density in Hong Kong is modest in comparison with other developed cities. However, decreasing internal densities in homes, i.e., more floor space per person, is a recent trend in Hong Kong. From 1981 to 1989, the average number of persons by home went from 3.9 to 3.6 (HKHA, 1994; Trueb, 1994). Nevertheless, the degrees of internal de-densification are modest. According to recent statistics, the average occupancy level remains about 3.5 persons per household, with 3.2 and 3.8 persons per household for private and public permanent housing respectively (HKHA, 1994), and the household sizes typically range from 50 to 80 square metres of gross floor area.
In Hong Kong, the average occupancy rate is thus estimated at about 15 to 20 square metres per person. Compact interior space still persists as a prevailing characteristic in most residential developments, in which design concerns always centre on high efficiencies in the use of interior space.

1.2.5 Building Density

For most building developments, especially in dense cities like Hong Kong, density is one of the major development control standards and often used as a key briefing target in urban planning and building design. Instead of population densities, building densities measured in term of plot ratios (PR) are more commonly used as the prime indicator in the day-to-day practice of building development and design, in which plot ratio (or floor space ratio [FSR]; floor area ratio [FAR]) basically refers to the ratio between the total gross floor area of a development and its net site area (see also Appendix 2: Glossary).

There are two main reasons for the preference to the measurement in term of building densities. Firstly, building densities are directly related to the extent of construction floor areas, and in turn the amount of resources (in terms of both financial resource such as construction price, saleable price, etc., and natural resource such as materials, energy, etc.) required for the construction. Therefore, building densities become a focus in design briefing and development budgeting.

Secondly, building densities have a close relationship with the physical form of building development, in particular its overall volume of building mass which has profound physical impacts on the urban environment. According to Hughes (1995a, 1995b), the increase of building density is one of the most significant factor shaping/restricting the possibilities of residential design, including master layout, built form, internal layout, etc.

In spite of the emphasis on plot ratio in the measurement of building densities, open space ratio is another key control standards in the development and design of residential estates. Open space ratio is commonly measured in term of unit area of open space per resident.
A lack of outdoor recreational space and facilities has been a frequent criticism on high-density housing developments. Therefore, an objective of the control on open space ratio is commonly to safeguard a reasonable minimum provision of outdoor leisure space and amenities in proportion to the size of resident population.

In contrast to the maximum plot ratio of 15 for commercial and industrial development, Hong Kong Building (Planning) Regulations stipulate a maximum of 10 for residential development in most urban areas. In conjunction with other planning and lease controls, the maximum permissible plot ratios for residential development tend to be lower (e.g., about a plot ratio of 5 to 8) in the new towns (Marsden, 1994; Pryor and Pau, 1993b). Nonetheless, as driven by the property market, almost all buildings take up the full permissible plot ratios unless they are rather old developments, have site problems, or are subject to special controls such as an airport height restriction (Lau and Lee, 1996, Marsden, 1994). The standards of open space for new housing estates generally stipulate a minimum of one to two square metres per resident within the development sites under Hong Kong Planning Standards and Guidelines.

1.2.6 High-Rise

High building density should not be simply confused with high-rise development. In the French language, *high density* [haute densité] is referred to whether it is the density of population or density of construction (in height). In English [and in this thesis], two terms are being used: *high density* and *high-rise* (Fouchier, 1994).

Theoretically, high buildings do not necessarily imply high densities of population or building, or vice versa (Gaitanakis, 1995). As a matter of fact, in contrast to the fall in population densities [as induced by the fall in occupancy densities], both the volume and height of buildings has continued to increase in Hong Kong. In addition, building height in itself is not generally controlled in Hong Kong and is not a public issue (Marsden, 1994).
Hong Kong is characterized by both high-rises and high densities of population and building. Provided that space standards (especially, occupancy density) are adequate, high-rise development allows activities to be stacked at convenient locations without internal crowding or congestion. Marsden (1994) describes,

"Hong Kong is distinctive in that many types of activities are in high-rise buildings, not just central commerce and very high- and low-status residential ... Hong Kong can be characterized as a 15-storey city, compared with, for example, Guangzhou/[Guangdong, China] 6-storey, Glasgow 3-storey and Melbourne 1-storey ... High-rise residential buildings appeared in the 1920s in New York. Hong Kong introduced widespread residential high-rise ...." (p. 34).

In Hong Kong, the widespread adoption of high-rise built form in residential development is primarily attributed to the notion of high building densities. According to Hong Kong Building (Planning) Regulations, the statutory schedule controlling development potential is in the form of a sliding scale allowing plot ratio to increase with building height but inversely with site coverage, which in effect encourages tall, thin buildings at higher building densities (measured in term of plot ratios). For instance, for a residential development with a plot ratio of 10, the site coverage of the residential towers is restricted to 40 percent in total. This results in a building height of at least 25 storeys. The objective of the current legislation is that the building form has to allow for the penetration of natural light and air to the habitation rooms as well as the open space and street around the building for reasons of public health, and such control is made by restricting the percentage of the site covered by the base area of the building, in particular the tower block(s). Moreover, the planning standards on open space aim at ensuring that the provision of minimum outdoor leisure areas is not compromised in dense residential developments. Consequently, the current high-density housing developments are predominately in the form of high-rises between thirty and forty storeys. One of the common residential building type is the slim, pencil-like point block typically with eight or fewer apartment units per floor in a cruciform layout where a central service core is surrounded by dwelling units at four sides (Hughes, 1994a; Lau and Lee, 1996; Sullivan, 1994). (See also Section 1.3.1).
1.3 HOUSING IN HONG KONG

1.3.1 Built Form

Dwelling densification is closely related to the building form, although high density does not necessarily imply high-rise or vice versa. A number of high-density housing typologies have been evolved since the urbanization of Hong Kong started in the 1840s. The key building typologies include "row houses" of about 5 storey (built before 1960s), "massive blocks" of about 10 to 20 storeys (built between the 1950s and 1980s), and "towers" of about 30 to 40 storeys (built since the 1970s), which typically accommodates about 2,300, over 5,000, and about 2,500 persons per hectare of net site area (Sullivan, 1994).

Currently, a predominant "sub-type" of the residential towers is the slim, pencil-like point block typically with eight apartment units per floor in a cruciform layout plan where a central service core (housing lifts, stairs, service risers, refuse chutes, etc.) is surrounded by dwelling units at four sides. In this configuration, bedrooms and living rooms of the residential units are usually arranged on the exposed sides of the building in order to maximize light, view and ventilation, while kitchens and bathrooms are tucked out of sight in the "reentrants". Figure 1.4 shows the archetypal cruciform floor plan in a point block tower. Lau and Lee (1996) describes,

"one of the most important concerns for Hong Kong's developers is the wish to develop a site to its maximum legal limits, especially in terms of its money-making GFA [gross floor area]. As such, the typical floor plan of high-rise residential buildings has been 'perfected' through the years to an archetypal cruciform design ... which is the most efficient plan-form to achieve the maximum GFA." (p. 82).

1.3.2 Urban Form

The urban form of Hong Kong has also been evolving. In the era of row houses and massive blocks, private-sector residential development was characterized by individual buildings erected on small pockets of land arranged in linear patterns that followed the layout of the street grids. For row houses, the basic lots typically measured 4.5 metres wide and 16 metres deep, resulting in a narrow street frontage and almost full site coverage by building.
FIGURE 1.4  
TYPICAL FLOOR PLAN OF HIGH-RISE RESIDENTIAL BUILDINGS IN HONG KONG

"reentrant"
(hanging clothes for drying; installation of individual air-conditioners, etc.)
Through amalgamation of the basic lots, massive blocks were usually built on larger sites, but were still characterized by a very high percentage of site coverage. Many of them still exist in the Metro area. With the launch of the "new town programme" in Hong Kong in the 1970s, large parcels of land have become more easily available for comprehensive housing development in form of residential estates (Pryor and Pau, 1993). Through large-scale urban renewal programme, redevelopment sites also provide the emergence of large residential estates in the old urban areas. The residential estates are commonly characterized by large sizes of site area measured in unit of hectares, and composed of a number of point block towers and other neighborhood amenities surrounded by landscaped open space, instead of street grids. Figure 1.5 shows a typical residential estate in Hong Kong.

1.3.3 Housing Densities

High-density, high-rise residential estate is currently the norm in both private- and public-sector developments in Hong Kong. The population density is commonly about 2,500 persons (or 650 household units) per hectare of net site area, but varies in a typical range between 1,500 persons (400 household units) and 4,500 persons (1300 household units) per hectare. Despite the tallness of the buildings, the contemporary residential estates generally have lower residential densities than the older built forms such as massive blocks (in which the corresponding densities can be as high as over 5,000 persons per hectare). The difference is largely because of the shift in occupancy densities, i.e., there are on average more floorspace available per person in recent developments. The current occupancy rate is typically 15 to 20 square metres of gross floor area per resident. On the other hand, domestic building can be developed to a maximum building density at a plot ratio of 10 under Buildings Ordinance. Particularly in the Metro area where individual building sites are commonly small, the developments always maximize the plot ratio up to 10. However, under the recent planning policy, the building density of large residential estate development is usually lowered to a domestic plot ratio of about 5 to 8, with open space provision at a minimum of one square metres per resident (two square metres per resident in the new towns).
FIGURE 1.5  TYPICAL HIGH-DENSITY RESIDENTIAL ESTATE IN HONG KONG
1.3.4 Summary: Dwelling Archetype

In this thesis, the prevalent form of private-sector residential estate development in Hong Kong represents the archetype of its high-density dwelling for assessment and comparison with the dwelling archetype (or dwelling model) in other cities. Although the emphasis of the analysis is placed on the effects of occupancy density, building density and net residential density, the implications of other major physical characteristics of the dwelling archetype should also be understood in conjunction with the densities quoted. In sum, Hong Kong's high-density dwelling archetype is basically characterized by the following densities and development parameters:

- The net residential density is approximately 2,000 to 4,000 persons per hectare site area.
- The building density is in the order of plot ratio 5 to 10.
- The occupancy rate is approximately 15 to 20 square metres gross floor area per person.
- The open space ratio is in the order of minimum one to two square metres per person.
- There is about 3.5 persons per household, or 50-80 square metre floor area per household.
- The typical building height is about 30 to 40 storey tall.
- The point block apartment tower represents the most common residential building form.
- The development site area is usually in the order of over one hectare.

The size of some large development sites are currently in the order of 20 to 30 hectares. Thus a residential estate in Hong Kong can typically accommodate about 2,500 to over 30,000 residents, or about 650 to over 10,000 dwelling units -- resembling the scale of a small town or city in Europe and North America. The current archetype of residential estates in Hong Kong are in effect "vertical towns", as a result of high levels of dwelling densification (Marsden, 1994). Conceptually, Hong Kong could thus be seen as a metropolis comprising several hundreds of these "vertical towns", which accommodate a total population of some six million.
2.1 CATEGORIZATION OF RESOURCES

2.1.1 Overview

When a person moves from a city to another, his or her consumption patterns are inevitably influenced by the new physical and social context. The built environment has direct and indirect physical effects (in terms of constraints and/or opportunities) on the patterns of daily living and in turn the patterns of human consumption. According to Wackernagel (1994), the challenge of human communities is to develop a physical environment with "infrastructure" that leaves options open, rather than one which dictates resource-intensive lifestyles for the present and future generations. However, at both very high and very low residential densities, density tends to become a predetermining parameter that creates constraints upon the feasible range of design solutions, and in turn upon the possible characteristics and performance of the settlement, including its degrees of resistance to minimizing human impacts on the carrying capacity of the planet. Lynch (1981) suggests in Good City Form, "the world can be seen as a system of polarities -- hot and cold, big and small, black and white, high and low -- and danger is expected at each end of the spectrum." (p. 370).

For example, people living in North American cities (i.e., the typical spread cities with the majority of population living in suburbs) are usually associated with high per capita consumption of gasoline, largely due to their "need" for dependence on private automobile (which is comparatively energy inefficient); they also frequently have high per capita consumption of potable water as a result of the "need" to irrigate the lawn and plants of their private gardens (Newman and Kenworthy, 1989). However, they have an "option" to reduce their per capita generation of household organic waste to be disposed of at landfills through backyard composting; they further have an "option" to grow some of their own food in the backyard.
In contrast, the people living Hong Kong (i.e., a compact city with the majority of population living in high-rise apartment buildings) typically have low per capita consumption of fossil fuels for daily commuting, due to the possibility of using an efficient public transportation network in conjunction with the frequently available "option" of traveling on foot; they also commonly consume less potable water as the demand of water for gardening is reduced through the efficiency of communal management of open space in residential estates. However, they mix their household organic waste together with other recyclable and non-recyclable wastes in their garbage bin for disposal, since the "option" of having an appropriate space for waste segregation and composting by individuals is usually unavailable.

In addition to the concern about "options", the efficiency of resource use is another key issue. However, the term *efficiency* is meaningless, until the scope of basic values is defined. Efficiency is described as the trade-off criterion between different values -- some of them internal to the theory, and some external to the list of criteria under consideration (Lynch, 1981).

Increasing energy efficiency in buildings is a typical concern in the industrialized region. A large amount of research has been done in this respect since the energy crisis in the early 1970s. The scarcity of energy (especially, fossil fuels) has been primarily concerned, while the other values such as the efficiency in using material, water, or land resource may have been traded-off, or compromised. Nowadays, the environmental crisis is considered more complex. In addition to energy conservation, the need for conservation of water and material resources are critical requirements. In this study, *efficiency* is measured with respect to the usage pattern of energy, water, and material resources (including the treatment pattern of liquid and solid wastes) on a per capita basis.

This thesis attempts to develop a framework of analyzing the *efficiency* of resource use that is subject to the influence of dwelling densities. The patterns of resource use are categorized into three main groups: (1) energy, (2) water, and (3) material.
Energy use is central to addressing the environmental agenda relating to key global issues like climate change, and regional/local issues like acid rain and air pollution (Cole et al., 1993). Potable water is a vital yet commonly abused resource, especially in cities (Vale, 1991). The use of materials, both renewable and non-renewable resources, has environmental costs; the prudent and selective use of materials and the recovery of "waste" materials (from wastewater and solid waste streams) form the important components of environmental conservation. Both the "input of resources" and the "output of wastes" are in need of concerns. From an ecological perspective, both the "sources" and the "sinks" are limited -- a source is where resources are derived; a sink is where wastes are put (Girardet, 1992). Jacobs (1992) contends that the industrialized cities are frequently the agents that transform sources into sinks with little regards to the natural capacity of resource regeneration and waste assimilation; this process characterizes a degenerative system that continuously diminishes the earth's ability to support healthy ecosystems, and pollution control and other mitigation only soften [local] problems but not change the global degenerating patterns.

Figure 2.1 shows a matrix of the relationships between dwelling densification and the "indicators of greenness". It places the "indicators of dwelling densification" against the "indicators of greenness". The former is composed of (1) occupancy density, (2) building density, and (3) residential density, whereas the latter is categorized into (1) energy, (2) water, and (3) material. As illustrated later, each of these key resource categories is further divided into a number of "components" of resource use -- which cover not only the aspects of resource input required for building and daily living needs, but also the associated patterns of waste generation/treatment. It is useful to develop a framework of categorization for the purpose of assessment.

Another important issue is concerned about the interconnectedness and overlaps between the categories of resource use (e.g., the linkage between domestic water use and energy consumed for water heating and pumping). These interrelationships should be recognized, although they are not the focus of this study.
### "INDICATORS OF DWELLING DENSIFICATION"

<table>
<thead>
<tr>
<th></th>
<th>Occupancy Density</th>
<th>Building Density</th>
<th>Residential Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>&quot;INDICATORS OF GREENNESS&quot;</td>
<td>Water</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Material</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**FIGURE 2.1** INITIAL MATRIX OF RELATIONSHIP BETWEEN DWELLING DENSIFICATION AND "INDICATORS OF GREENNESS"
2.1.2 Energy

In the contemporary industrialized cities, both the housing development and occupation/daily activities are heavily dependent on the consumption of fossil fuels. From a life-cycle assessment approach, the energy use related to the initial construction, recurring maintenance and ultimate removal of building and the daily operational needs of dwellers can be categorized into five distinct aspects.

- **INITIAL EMBODIED ENERGY**
  A substantial amount of energy is involved in the extraction of raw materials, and manufacture, transportation and installation of building components in the initial production of housing stock. Initial embodied energy typically describes the energy required to initially produce a building.

- **RECURRING EMBODIED ENERGY**
  Energy is required to maintain and refurbish a building over its effective life-span. In this study, the average life-span of building is assumed to be about 50 years. Maintenance and replacement occur periodically over the life of a building. Maintenance is assumed to involve replacing less than 100 percent of a material or component, whereas replacement refers to the total replacement (100 percent).

- **OPERATING ENERGY**
  Energy is required for the daily operation of a building, such as space conditioning, electric lighting, and water pumping. The level of energy consumption varies considerably with geographic (e.g., climate and season), social (e.g., habits and environmental awareness) and architectural (e.g., building and system design) factors. In this regard, it is useful to distinguish between those aspects of operating energy which are directly influenced by the architectural design and those which are primarily dependent on the other factors such as personal choice.
The former refers to operating energy use such as space cooling which is largely influenced by spatial layout and envelope design of a building; the latter refers to the use of household appliance like TV, which is determined by occupants lifestyle but largely independent of the buildings characteristic. This thesis focuses on the first group of operating energy use.

- COMMUTING ENERGY

Energy is also used for vertical movement (e.g., lift and escalator) and vehicular transportation (e.g., car and transit) by dwellers between places of home and work, shopping, and entertainment. In dense, mixed-use developments, residents living in upper floors travel to local shops at low levels by lifts (which is equivalent to the use of cars in low-density suburbs). Similar to the operating energy of a building, the commuting energy use depends on a multitude of variables including built form, climate, and socio-economic factors. Nonetheless, the correlation between the consumption level of commuting energy and urban density -- which is in turn closely dependent on dwelling densities -- is evident among the industrialized cities (Newman and Kenworthy, 1989; Wackernagel, 1994). Dwelling densities and the corresponding building design are considered prime physical factors influencing the mode of people movement system, and hence the level of per capita energy consumption.

- DEMOLITION ENERGY

Energy is used to demolish buildings, and transport and dispose of "waste" materials at the end of its effective life. Current demolition practice involves intense application of energy and haulage to landfills.

This analysis emphasizes those aspects have a close relationship with architectural design. The energy use related to the infrastructure serving residential area (e.g., the initial and recurring embodied energy of main road construction and transit system) has not been taken into account. There are scopes for research, though. Nonetheless, at higher density, the per capita resource use associated with urban infrastructure is commonly lower (e.g., Marsden, 1994; Walker, 1995).
2.1.3 Water (& "Wastewater")

There are two interconnected environmental concerns: (1) conservation of potable water, and (2) reclamation of "wastewater" available on-site. Water, particularly potable water, is a vital resource for human existence and daily living. As pointed out Athens and Ferguson (1996),

"the amount of water available for use on the planet is finite ... as population grows, the available supply of water per person drops. Per capita water supplies worldwide have decreased by one-third since 1970, as the world's population has grown by 1.8 billion ..." (p. III.18).

While water is consumed for a variety of domestic use, "wastewater" is subsequently discharged. As pointed out by Hough (1995), along with the use of water resource there are enormous nutrient and other resources as the by-products of urban drainage and sewage disposal systems; sanitary sewers and the like break the life-cycle of nutrient and materials of natural systems. Vale (1991) further assert, "sewage ... a resource to be used beneficially rather than a waste to be dumped in the sea where it creates further problems." (p. 25). To optimize the use of water resource and the reclamation of nutrients contained in the household effluent, the treatment and recycling of "wastewater" on-site is hence examined in this study. The harvesting of rainwater, another under-utilized water resource which is commonly conceived as "waste" and dumped via drains quickly, is also explored. There are five categories of concern with respect to urban household water (and wastewater) use:

- **POTABLE WATER USE**

Potable water is essential for various domestic use, such as drinking, cooking, bathing, washing, etc. However, in the contemporary society, there is seldom any distinction made between water that is intended to be drunk and water that is used for many other purposes connected with buildings (Vale, 1991). "High-grade" potable water is commonly utilized for toilet flushing and irrigation, which is unnecessary from an environmental perspective. In this study, potable water use is hence confined to the indoor water use at home, excluding water used for flushing and other outdoor use such as landscape irrigation.
• FLUSHING WATER USE

As forth mentioned, potable water is commonly used for toilet flushing. With greater concentration of people, the question of hygiene assumes serious concern, especially for cities in the tropics. With the use of water closet, water is used as a medium to convey human waste discharged away from a dwelling place. As contended by Parikh and Parikh (1990) and Van der Ryn (1978), the contemporary design of sanitary system requires considerable quantities of water, and consequently creates both waste disposal problem and resource-scarcity problem. From an environmental perspective, both the use of potable water for flushing and the disposal of sewage (a nutrient-rich resource) are wasteful practice. Alternative water source such as sea water or treated greywater can be utilized for flushing, whereas blackwater can be treated and recycled for beneficial use (Athens and Ferguson, 1996).

• IRRIGATION WATER USE

Landscape area is commonly an essential component of dwelling environment. The ownership and management of residential landscape area varies with dwelling densities. At high residential densities like those prevalent in Hong Kong, the open space is mostly a common area; in North American suburbs, each house typically has its own garden. For a given garden area, the use of irrigation water varies with climate and micro-environment, selection of species, and ownership and management of open space. According to Newman and Kenworthy (1989), private lawn and garden watering is by far the biggest consumer of water in cities like Perth, Australia, where spatially lavish suburbs use some 4 to 5 times as much water as do the medium density suburbs; less private space and more public space can be a significant factor in determining water policies. In addition to the issue of garden size, house owners frequently nourish their private garden with excess water, whereas watering is usually managed more prudently in residential estates. On the other hand, as pointed out by Sorvig (1996), using processed city water for irrigation is wasteful, since plants do not require potable water, and are often vulnerable to chlorine.
• WASTEWATER RECLAMATION

Both the potable and flushing water use generate "waste" effluent, which can be categorized into greywater and blackwater. Greywater refers to the wastewater generated from indoor use such as showers, sinks, etc., whereas blackwater mainly refers to the wastewater discharged from toilets or urinals. Despite their difference in composition, they are usually mixed together and disposed of via a single piping and treatment system (Stein and Reynolds, 1992). Conventional, centralized sewage treatment plants require large inputs of energy, resources, and chemicals. The treated effluent is discharged into waterways or the sea, causing environmental degradation in the coastal and aquatic ecosystems. As advocated by Athens and Ferguson (1996), alternative, decentralized wastewater systems using biological treatment can help minimize the environmental impacts and reduce the use of chemicals. Household wastewater is potentially a resource which can be reclaimed for beneficial use. Water diverted from the waste stream can be either greywater or blackwater, which require different on-site handling. In this study which is concerned with water conservation and nutrient recovery, the reclamation of both greywater and blackwater is thus examined. The resulting treated effluent can be utilized on-site for non-potable purposes such as toilet flushing or irrigation, reducing unnecessary demand for high-quality potable water.

• RAINWATER HARVESTING

In cities, rainwater falls on building roof and imperviously paved area. A drainage system is usually provided to discharge the runoff to prevent the threat of flooding in the urban area. Although rainwater is potentially a natural site resource for use, it is largely seen as "waste" which is discharged and disposed of from the dwelling place.

The production of building materials and components, and the construction, maintenance and demolition of buildings also require a prodigious quantity of water (Vale, 1991). However, the scope of this study is confined to the patterns of water use and wastewater reclamation related to daily domestic operations, which represent the predominant concerns in cities.
2.1.4 Material

For initial housing construction, materials are used for the assemblage of building components. In the construction process, materials for temporary use (such as timber hoarding and concreting formwork) are used, and waste materials (including excavated earth, surplus and package materials) are generated. Similarly, the maintenance and refurbishment of building involves the input of materials and the output of waste materials. At the end of the building life-span, the demolition usually generates enormous amount of waste materials.

Households also generate a large quantity of solid waste materials daily for disposal. Broadly speaking, the household solid wastes can be divided into two aspects: firstly, inorganic materials such as aluminum cans, plastic containers and bags, and glass bottles; secondly, organic materials including kitchen scraps and other putrescibles. In view of the above, it is useful to distinguish the patterns of material resource use into five aspects:

- INITIAL BUILDING MATERIAL USE

Various kinds of material are required for the initial construction of buildings, including the materials for temporary construction purpose like concreting formwork and proppings. Waste materials are subsequently generated in the process of construction. The materials can be further categorized into two groups according to their source: (1) the renewables, and (2) the non-renewables. Renewables primarily refer to timber products. However, the current rate of consumption incurs environmental concerns with respect to the depletion rate of their source (e.g., forests) and the other ecological impacts, including the loss of biological diversity (e.g., due to depletion of tropical rainforest) and global warming (due to increasing carbon dioxide levels in the atmosphere as a result of deforestation) (Dayal, 1990). Non-renewables refer to materials like metals which have a finite source. An environmentally responsive approach is to conserve both the renewable and non-renewable resources, and prolong their useful life by recycling and reuse.
• RECURRING BUILDING MATERIAL USE

Materials are required for refurbishment and maintenance over the effective life of a building. In general, the finishes, internal fittings and fixtures, partitions and doors, and building services are replaced, refurbished and maintained more frequently than the structure and envelope of the building.

• DEMOLITION WASTE GENERATION

Large quantities of solid waste are generated from building demolition. The amount and composition of demolition refuse varies with building types and design. Current demolition practice typically involves intense application of machinery and various "waste" materials are mixed together for disposal in landfills. However, salvaging of materials for recycling and reuse assume greater importance as increasingly driven by various forms of legislation and economic incentive (such as increasing charge for waste disposal in landfills and increasing economic value of salvaged materials).

• HOUSEHOLD INORGANIC WASTE RECOVERY

Household inorganic solid waste is typically composed of metals, plastics, glass etc.. In this study, paper waste is included in this category, since its recycling process is similar to that of other inorganic wastes. The ratio between household inorganic and organic wastes varies with occupants lifestyle; however, in industrialized cities, the household inorganic waste on average accounts for about 60 to 70 percent by fresh weight.

• HOUSEHOLD ORGANIC WASTE RECOVERY

Household organic solid waste primarily refers to the putrescibles (food waste, etc.) generated from household kitchens. It also includes the organic waste from gardens, particularly in the case of detached single-family house which has an extensive landscaping area. Composting is a primary method to reclaim useful materials from the organic waste.
2.2 MATRIX OF ASSESSMENT

2.2.1 Modules of Assessment

The level of greenness is reflected in the per capita usage pattern of natural resources including energy, water, and materials associated with the construction of buildings and the operational need of dwellers. At the same time, dwelling densification is examined with respect to the indicators including occupancy density, building density, and residential density on the scale of individual housing developments.

Figure 2.2 shows an expanded matrix of the relationship between dwelling densification and the "indicators of greenness". The matrix expands to have fifteen modules under each indicator of dwelling densification. Each of these modules represents the relationship between an indicator of dwelling densification (e.g., occupancy density) and a "sub-indicator of greenness" (e.g., initial embodied energy). To assess the levels of greenness and the relative significance of individual components, quantification is considered a useful tool of evaluation, in particular for the two following basic concerns:

• HIERARCHY OF COMPONENTS OF RESOURCE USE

For instance, the amount of energy use associated with building demolition typically represents about one percent of the total energy consumption based on a building life-cycle analysis (Cole and Wong, 1996). In contrast, the amount of energy consumption related to operational needs is typically much higher. Through quantifying per capita consumption due to each component of resource use, a hierarchy of significance can be developed.

• CONSUMPTION LEVEL OF DWELLING MODEL AT VARIED DENSITIES

It is useful to highlight the various aspects of density dependence (and their degrees of dependence) through a comparative study on the consumption levels of energy, water and material associated with the dwelling model at high and low dwelling densities.
## INDICATOR OF DWELLING DENSIFICATION

<table>
<thead>
<tr>
<th></th>
<th>Occupancy Density</th>
<th>Building Density</th>
<th>Residential Density</th>
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</thead>
<tbody>
<tr>
<td><strong>ENERGY</strong></td>
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<tr>
<td>Initial Embodied Energy</td>
<td>...</td>
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<tr>
<td>Recurring Embodied Energy</td>
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<tr>
<td>Operating Energy</td>
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<td>...</td>
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<tr>
<td>Commuting Energy</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Demolition Energy</td>
<td>...</td>
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<tr>
<td><strong>WATER</strong></td>
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<tr>
<td>Potable Water Use</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Flushing Water Use</td>
<td>...</td>
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<tr>
<td>Irrigation Water Use</td>
<td>...</td>
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</tr>
<tr>
<td>Wastewater Reclamation</td>
<td>...</td>
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<td>...</td>
</tr>
<tr>
<td>Rainwater Harvesting</td>
<td>...</td>
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<tr>
<td><strong>MATERIAL</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Initial Building Material Use</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Recurring Building Material Use</td>
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<tr>
<td>Demolition Waste Generation</td>
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</tr>
<tr>
<td>Household Inorganic Waste Recovery</td>
<td>...</td>
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<tr>
<td>Household Organic Waste Recovery</td>
<td>...</td>
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<td>...</td>
</tr>
</tbody>
</table>

**FIGURE 2.2** MATRIX OF RELATIONSHIP BETWEEN DWELLING DENSIFICATION AND PATTERNS OF RESOURCE USE
2.2.2 Quantification

Different but consistent units of measurement are used for assessing energy, water, and material resources. The basic units of measurement to be adopted are GJ/person/year, litre/person/day, and kg/person/year for the use of energy, water, and material resources respectively.

Some current research are attempting to combine the various categories of human consumption, including land, energy, water, material use etc., into a common unit of measurement. An example is the concept of "ecological footprint": an ecological accounting tool that uses biologically productive land area as its measurement unit (Wackernagel, 1994). The adoption of a unified measurement of environmental impact has the merit of linking the use of different resources, so that the relative levels of environmental impact can be compared among the use of various resources, and more importantly, with the carrying capacity of the planet. According to Wackernagel and Rees (1996), the per capita biologically productive land available on the planet that supports human living with supply of energy and other resources and absorption of waste discharged is currently estimated at approximately 1.5 hectare. This figure is diminishing as a result of increasing world population, deforestation, desertification and urbanization etc. However, in term of "ecological footprint", the current per capita consumption levels among the industrialized countries amount to approximately 5.1 hectares, 4.3 hectares, 3 hectares, and 2 hectares in the United States, Canada, Western European countries (such as Britain), and Asian countries (such as Japan) respectively. All of these "advanced" countries have a significant ecological deficit.

On the other hand, Walker (1995) compares the "ecological footprints" of Canadian households living in various dwelling types and densities, based on an assessment of resource (land, energy, and material) consumption for housing, transportation, and infrastructure. The results demonstrate that, in Canada, detached single-family house has the largest ecological footprint (about 1.5 hectare) per capita whereas high-rise apartment has the smallest (about 60 percent of the detached house value).
The resource consumption measured in term of "ecological footprint" seemingly correlates with
the levels of densification among the industrialized cities: the higher the population densities, the
lower the per capita "ecological footprint". Although this measurement is beyond the scope of this
thesis, it presents a meaningful topic for future research. For instance, What is the average per
capita "ecological footprint" in Hong Kong, one of the most dense industrialized cities? Or, what
is the "ecological footprint" associated with Hong Kong's high-density apartment building?
Nevertheless, the emphasis of this study is placed on a separate evaluation of individual resources,
and different accounting units are hence adopted for measuring the usage levels of energy, water
and material resource. The establishment of data can be seen as a primary source of findings. In
future research, it could be translated into another form of indicator of environmental impact, such
as "ecological footprint" if the inter-resources linkage were to be considered necessary.

• ENERGY

"MJ (or GJ)/person/year" is used as the basic unit for accounting the levels of energy
consumption. Energy audits have the relative simplicity of being reducible to a common
energy unit for evaluation. For a life-cycle analytical approach, the life-span of a building has
to be defined at the outset. In practice, the effective life of a building varies with its
construction method and standards, maintenance, and functional/spatial adaptability. Land
use and planning policy and other socio-economic factors also have a role in determining a
building's life-time. In this thesis, the notional life-span of a building is assumed to be 50
years. (In Hong Kong, many of the residential buildings developed in the 1950s and 1960s
were designed and built expeditiously to meet the demand of a rapidly increasing population,
and hence quickly become obsolete in terms of space and functional standards. Many of them
have been already demolished, and their effective life-time has been only about 20 to 30
years. Nevertheless, it is a reasonable assumption for the current stock of housing mostly
developed since the 1980s in Hong Kong to have an effective life-span of 50 years, given the
improved standards of housing design, construction, and management.)
- WATER

"Litre/person/day" is adopted as the basic unit to measure the quantity of recurring water consumption and wastewater discharge. The level of water consumption and wastewater (and rainwater) discharge varies with season. Therefore, the notional data on a daily basis used in this study are derived from the average quantities over a year.

- MATERIAL

"Kg/person/year" is used for the measurement of material consumption and solid waste generation. (The data of household solid waste is also presented on a "per day" basis as a supplementary reference.) For a life-cycle analysis, a building’s life-span is assumed at 50 years as discussed above. Both the material input and waste output are divided as an average on a per capita-year basis. Two other analytical methods are concerned. First, instead of the measurement by weight, the volume of materials and wastes are sometimes adopted in other research. A problem about the measurement by volume is that many materials and solid wastes are compressible. Sometimes, there are mechanical compressors to condense the volume of solid waste to facilitate waste delivery from residential estates to municipal refuse depots and landfill sites. The reason is that the capacity of refuse transportation is largely determined by weight of the waste. Second, there are complexities in the environmental impact of various materials, given that they are of similar weight or volume. Embodied energy can be a useful indicator with regard to the environmental impact associated with material use, but a host of other key environmental impacts are less quantifiable. The use of hardwoods from tropical rainforests, for instance, causes profound environmental concerns including loss of biodiversity, climate change, etc. The extensive use of concrete and steel in high-rise construction not only results in high levels of initial embodied energy per unit floor area, but also involves high levels of carbon dioxide emissions and water consumption in the production processes. Such environmental impacts associated with material use require special qualification in addition to the analytical technique of quantification.
2.2.3 Density-Dependence

In the analysis of the relationship between dwelling densification and resource use, there are some particular points of concern for examination. The framework of assessment is used to examine the following three key issues:

• **RELEVANCE TO DENSITY-DEPENDENCE**
  
  Through the process of quantification, the relative significance of individual components of resource use can be evaluated. Through the comparative study on the dwelling archetype at different densities, the density dependence of individual components of resource use can also be revealed. Overall, the analysis aims at identifying the key components of resource use that show "high relevance" to density dependence. The others which are relatively minor and largely independent of the effect of dwelling densities are thus classified as "low relevance".

• **CHARACTERISTICS OF DENSITY-DEPENDENCE**
  
  According to Newman and Kenworthy (1989), for instance, the consumption of commuting energy is highly dependent on urban densities [which is in turn dependent on residential densities directly, but occupancy density indirectly]. For different components of resource use which show high relevance to density dependence, their "characteristics" of density dependence vary. Some of them are subject to the direct effects of dwelling densification on the upper scale of reference, e.g., residential density instead of occupancy density. Others are directly dependent on occupancy density, building density, as well as residential density.

• **OPPORTUNITIES OR CONSTRAINTS**
  
  The effects of density dependence can contribute to varied levels of per capita consumption of natural resources, and in turn the extents of environmental impact. An objective of this thesis is to identify both the "positive" and "negative" implications of Hong Kong's high-density housing on the carrying capacity of the planet, i.e., the opportunities and constraints of Hong Kong's high-density housing that reduce or increase per capita levels of environmental impact.
2.3 MODEL FOR COMPARISON

2.3.1 Model Selection

The general pattern of dwelling densities among industrialized international cities has been examined in Introduction. Hong Kong, a compact, industrialized city, has the highest dwelling densities, whereas North American (and Australian) cities, the typical spread, industrialized cities, rank the lowest. The typical suburban single-family house in North America (Canada and the United States) is proposed as the primary reference model in contrast with the high-density housing archetype in Hong Kong. In Canada and the United States, detached single-family house is the dwelling archetype, currently constituting 60 to 70 percent of the existing housing stock (Statistical Abstracts of the United States, 1989, in Chiras, 1992; CMHC, 1994, in Shawkat, 1995).

It is recognized that per capita consumption is also subject to other variables such as local climate, culture, and environmental policy, even though the standards of living were similar between the model cities. Stein and Reynolds (1992) describes, "[North American] society uses more energy per capita than most other countries, even some that have 'high standards of living' and colder winters than [those in North America]." (p. 3). Nevertheless, care should be made in analyzing and comparing the levels of per capita consumption, especially those aspects prone to the overriding influence of climate, lifestyle, etc. (A city-to-city comparison [e.g., Hong Kong versus Miami, which have similar climatic patterns] may have been an alternative study approach if the practical concern about availability and reliability of data can be handled.)

The example of North American cities includes Chicago in the United States and Vancouver, B.C., in Canada, where the typical residential building form is the detached single-family house of two storeys. Private open space with soft landscaping is commonly available around each house. The structure is typically a wood-frame construction with expected life-span of about 50 years (Walker, 1995). Figure 2.3 shows a typical layout plan of the detached single-family dwellings in North American cities.
FIGURE 2.3  TYPICAL LAYOUT PLAN OF DETACHED SINGLE-FAMILY DWELLINGS IN NORTH AMERICAN CITIES
2.3.2 Dwelling Densities & Characteristics

Table 2.1 compares the dwelling densities between the prevalent high-density housing in Hong Kong and the typical single-family dwelling in North American cities. The comparative characteristics of dwelling densities and other housing development aspects are as follows:

- **NET RESIDENTIAL DENSITY**
  The net residential density is respectively 2,000 to 4,000 and 50 to 75 persons per hectare of site area, i.e., in a ratio of about 50 to 1.

- **BUILDING DENSITY**
  The building density in term of plot ratio is 5 to 10 and 0.5 to 0.6 respectively, i.e., in a ratio of over 10 to 1.

- **OCCUPANCY DENSITY**
  The occupancy rate is respectively 15 to 20 and 50 to 100 square metres gross floor area per person respectively, i.e., the occupancy densities are in a ratio between 3:1 and 5:1.

- **OPEN SPACE RATIO**
  The open space availability is respectively 1 to 2 and about 100 square metres per person, i.e., in a ratio ranging between 1 to 100 and 1 to 50.

- **HOUSEHOLD SIZE**
  The household size is respectively about 3.5 and 3 persons per household, or 50 to 80 and 160 to 300 square metre floor area per household.

The above physical/spatial differences between the dwelling archetype in Hong Kong and that in North American cities form the basis of assessment in the forthcoming chapters. Such data are inevitably subject to change over time e.g., from 1981 to 1989, the average number of persons by home in Hong Kong went from 3.9 to 3.6 (HKHA, 1994; Trueb, 1994). Nonetheless, the collection of data in this study represents the current prevalent dwelling situation in the respective cities, and can be seen as a data basis for further refinement in future research.
<table>
<thead>
<tr>
<th></th>
<th>URBANIZED AREA:</th>
<th>GROSS RESIDENTIAL AREA:</th>
<th>INDIVIDUAL RESIDENTIAL ESTATE/LOT:</th>
<th>INDIVIDUAL HOUSEHOLD UNIT:</th>
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<tr>
<td><strong>Urban Density</strong></td>
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<tr>
<td>(persons per hectare land area)</td>
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<tr>
<td><strong>Gross Residential Area Density</strong></td>
<td>300 to 400</td>
<td>1000</td>
<td>2000 to 4000</td>
<td>5 to 10; 1 to 2</td>
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<tr>
<td><strong>Net Residential Density</strong></td>
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<tr>
<td>(persons per hectare of net site area)</td>
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<tr>
<td><strong>Building Density; Open Space Ratio</strong></td>
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<tr>
<td>(plot ratio; m² per person)</td>
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<tr>
<td><strong>Occupancy Rate = 1 / Occupancy Density</strong></td>
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<tr>
<td>(m² gross floor area per person)</td>
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<tr>
<td><strong>HONG KONG:</strong></td>
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<td></td>
</tr>
<tr>
<td>High-Density Multiple-Family Apartment Dwelling</td>
<td>300 to 400</td>
<td>1000</td>
<td>2000 to 4000</td>
<td>5 to 10; 1 to 2</td>
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<tr>
<td><strong>NORTH AMERICA:</strong></td>
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<tr>
<td>Low-Density Single-Family Detached Dwelling</td>
<td>20</td>
<td>30</td>
<td>50 to 75</td>
<td>0.2 to 0.6; about 100</td>
</tr>
</tbody>
</table>

Source: (Gaitanakis, 1995; Hughes, 1995a, 1995b; Marsden, 1994; Pryor and Pau, 1993b; Walker, 1995)
CHAPTER III
ENERGY-DENSITY RELATIONSHIP

3.1 INITIAL EMBODIED ENERGY

3.1.1 Overview

Although most of the current understanding of environmental costs of a building are related to the energy used to operate the building, there has been a recent renewal of interest and research into embodied energy. Over the life-cycle of a building, operating energy is commonly the largest energy use. However, as higher levels of building energy efficiency is introduced, the relative significance of embodied energy increases. Embodied energy is the sum of the "direct" and "indirect" energies used to manufacture, transport and install building materials and components. Direct energy is the energy actually consumed in the construction of buildings, whereas indirect energy is the energy consumed in the production of building materials and the associated transportation within the producer industry. In general, most of the energy embodied in construction is invested in the manufacture of materials and components (Cole and Rousseau, 1992; ERG, 1993; Stein and Reynolds, 1992). Embodied energy typically describes only the energy to initially produce a building and excludes the energy associated with maintaining and replacing materials and components over the lifetime of the building, hence the importance of using the designation initial.

According to the initial assessment of Hong Kong's typical point block residential tower by Cole and Wong (1996), the initial embodied energy is in the order of approximately 5 GJ per square metre of gross floor area. (In the assessment, car parking and podium structures which vary considerably in individual developments have been excluded from the evaluation of embodied energy.) Given that the current occupancy rate in Hong Kong is about 15 to 20 square metre per person and the notional building life-span is 50 years, the equivalent initial embodied energy on a per capita basis is hence approximately 1.5 to 2.0 GJ (or 1,500 to 2,000 MJ) per person per year.
On the other hand, the typical initial embodied energy of North American single-family houses is estimated at about 3 GJ per square metres of floor area (Lafrenière, 1994; Shawkat, 1995). As explained by Stein and Reynolds (1992), on a per unit floor area basis, single-family residences are relatively low in "energy intensiveness" in the construction phase; the primary reason is that they utilize so much wood in their construction, and wood is a low-energy material. For instance, the energy intensity of lumber is about 4 to 7 MJ/kg (Cole and Rousseau, 1991).

However, given the corresponding occupancy rate of 50 to 100 square metres per person and the typical building life-span of 50 years (similar to that in Hong Kong), the initial embodied energy on a per capita basis is as high as 3 to 6 GJ (or 3,000 to 6,000 MJ) per person per year.

3.1.2 Building Components

The construction process which covers all activities and processes associated with the erection of a building can be defined according to the following major aspects:

- Site-Work (site preparation, exterior landscaping and paving, service connections, etc.)
- Structure (formwork construction, foundation and sub-structure, superstructure, etc.)
- Building Envelope (external wall, glazing, roofing, finishing, etc.)
- Interior Finishes (ceiling, wall and floor finishes, partitions, stairs, fittings & fixtures etc.)
- Building Services (heating, ventilation and air conditioning [HVAC], plumbing and drainage, electrical, fire service systems, conveyance, etc.)

Table 3.1 compares the initial embodied energy associated with various construction aspects between Hong Kong's high-density housing and North American single-family dwelling. In the case of Hong Kong, structure, interior finishes, and building envelope represent the three largest sectors of initial embodied energy involved in the building construction, accounting for about 43 percent (650-900 MJ/person/year), 19 percent (300-350 MJ/person/year), and 18 percent (300-350 MJ/person/year) of the total initial embodied energy respectively.
TABLE 3.1  COMPARISON OF INITIAL EMBODIED ENERGY CONSUMPTION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE INITIAL EMBODIED ENERGY (MJ per person per year)</th>
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<tbody>
<tr>
<td></td>
<td>HONG KONG</td>
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<tr>
<td>Dwelling Archetype:</td>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT (building life-span = 50 years)</td>
</tr>
<tr>
<td>Site-Work</td>
<td>50 - 100</td>
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<tr>
<td></td>
<td>4 %</td>
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<tr>
<td>Structure</td>
<td>650 - 900</td>
</tr>
<tr>
<td></td>
<td>43 %</td>
</tr>
<tr>
<td>Building Envelope</td>
<td>300 - 350</td>
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<tr>
<td></td>
<td>18 %</td>
</tr>
<tr>
<td>Interior Finishes</td>
<td>300 - 350</td>
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<td></td>
<td>19 %</td>
</tr>
<tr>
<td>Building Services</td>
<td>200 - 300</td>
</tr>
<tr>
<td></td>
<td>15 %</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>1,500 to 2,000</td>
</tr>
<tr>
<td></td>
<td>(or 1.5 to 2 GJ/person/year)</td>
</tr>
</tbody>
</table>

Source: (Adapted from Cole and Wong, 1996; Lafrenière, 1994; Shawkat, 1995)
Evidently, in the case of high-rise buildings, the structure (including foundation, substructure, superstructure etc.) which utilizes a large quantity of energy intensive materials such as steel and cement becomes the dominant aspect of the construction. The energy intensities of steel and cement products are typically in the range of 25 to 35 MJ/kg and 5 to 10 MJ/kg respectively (Cole and Rousseau, 1991, 1992).

By contrast, in the case of North American single-family dwelling, building envelope, structure, and interior finishes are the three major sectors correspondingly, representing respectively 40 percent (1,200 to 2,400 MJ/person/year), 30 percent (900 to 1,800 MJ/person/year), and 17 percent (500 to 1,000 MJ/person/year) of the total initial embodied energy. The building envelope dominates the initial embodied energy of the building as a result of the high ratio between its envelope area and gross floor area, which is typically as high as 2 to 1 and above (Lafrenière, 1994). As a reference, the housing archetype of Hong Kong typically has an envelope-floor area ratio in the order of about one to one.

3.1.3 Observations

The quantitative assessment and comparison made on a per capita basis reveal the following key characteristics regarding the initial embodied energy of Hong Kong’s high-density housing archetype:

- **DEPENDENCE ON ENERGY-INTENSIVE MATERIALS**
  
  For the high-rise construction, steel and concrete are the common material choices for its structural components. The extensive use of reinforced concrete which is intensive in term of embodied energy per mass results in relatively high levels of initial embodied energy of the structure.

- **HIGH INITIAL EMBODIED ENERGY OF STRUCTURE**
  
  The structural component accounts for approximately 650 to 900 MJ/person/year, representing 40 to 50 percent of the initial embodied energy of the overall construction.
LOW PER CAPITA INITIAL EMBODIED ENERGY

Despite the energy intensiveness of its structure, on a per capita basis, the overall initial embodied energy of Hong Kong's high-density housing is only about 1.5 to 2 GJ/year, which is less than half of that associated with North American single-family dwelling (about 3 to 6 GJ/year). This implies that although wood, a less energy-intensive material, is extensively utilized in the construction of the single-family dwellings, the low occupancy rates (80 to 100 square metres of gross floor area per person) still turn out to be the predominating factor causing comparatively high levels of per capita initial embodied energy in the case of North America.

On the other hand, in the case of Hong Kong's housing, the high building densities lead to the widespread high-rise form of buildings and the use of energy-intensive materials for the structural components, and consequently high levels of initial embodied energy on a per unit floor area basis; however, the "positive" implications of its high occupancy rates (15 to 20 square metres of gross floor area per person) override the "negative" effects of its high building densities, and result in comparatively low levels of per capita initial embodied energy.

Residential density is a function of occupancy density and building density. In Hong Kong, the particular combination of high occupancy densities and high building densities results in high residential densities that have a correlation with relatively low levels of per capita initial embodied energy. As compared between the dwelling form of low residential densities in North America (50 to 75 persons per net site area) and the housing at high residential densities in Hong Kong (2,000 to 4,000 persons per net site area), the initial embodied energy on a per capita basis is in an approximate ratio between 2 to 1 and 3 to 1. Through the process of dwelling densification, the probable reduction in per capita initial embodied energy of housing construction can be substantial.
RECURRING EMBODIED ENERGY

3.2.1 Overview

Embodied energy represents the components or assembly in place. When a full life-cycle analysis is undertaken, embodied energy should be rightfully extended to include the energy associated with maintaining, repairing, and replacing materials and components over the lifetime of the building. In general, the interior finishes (including floor, wall and ceiling finishes, doors, partitions, fittings and fixtures, etc.) and building services are replaced, refurbished and maintained more frequently than the building envelope; the building envelope in turn requires more frequent maintenance than the building structure.

The significance of recurring embodied energy of a building increases considerably while the effective life-span of the building gets longer. For instance, the recurring embodied energy of Hong Kong's typical residential point block tower is estimated to be about 20 percent and 80 percent of its initial embodied energy for a building lifetime of 25 and 50 years respectively (Cole and Wong, 1996). The premise is that the effective lifetime of many building components lies between 25 and 50 years, so that there are usually more extensive maintenance and replacement of materials and components required for a building of lifetime exceeding some 25 years.

The analysis assumes that all future replacement materials are identical to those being replaced and their energy intensities are similar to the current levels with no allowance for improvements in manufacturing techniques over the intervening years. The estimated values of the maintenance and replacement embodied energy are therefore greater than will occur in practice, since the materials and construction processes can be anticipated to go through significant changes over decades. Nonetheless, in this section, the estimate based on a notional building lifetime of 50 years is largely conducted on a generalized theoretical level, and the data shown are preliminary. Further research with local survey data is recommendable in this aspect.
3.2.2 Estimation

For Hong Kong's typical residential point block tower, the embodied energy associated with repair and replacement of building elements over a building lifetime of 50 years is estimated at approximately 4 GJ per square metre floor area. About 70 percent of the total recurring embodied energy (i.e., approximately 3 GJ per square metre floor area) is attributed to the maintenance and replacement of interior finishes and building services; and about 20 percent (i.e., less than 1 GJ per square metre floor area) is related to the building envelope (Cole and Wong, 1996). On a per person basis, the recurring embodied energy associated with Hong Kong's high-density housing over a 50 year life-span of the building is hence estimated at the order of 1 to 1.5 GJ (or 1,000 to 1,500 MJ) per person per year.

For the North American single-family dwellings, it is reasonable to anticipate that the interior finishes and building services together constitute the major sector in the recurring embodied energy. As shown in Table 3.1, the initial embodied energy of these two components in the dwelling archetype between North America and Hong Kong (650 to 1,300 MJ/person/year and 500 to 650 MJ/person/year respectively) are in a ratio between 1.3 to 1 and 2 to 1. By pro rata, the recurring embodied energy of a typical North American single-family dwelling over a 50 year life-span of the building is estimated at approximately 2 to 3 GJ (or 2,000 to 3,000 MJ) per person per year, i.e., about half to two-thirds of its initial embodied energy.

This figure closely corresponds to the assessment of Shawkat (1995) in which the recurring embodied energy of a typical Canadian single-family house is estimated at approximately 44 percent and 63 percent of its initial embodied energy over a 40 year and 60 year life-span respectively. For 40 year life cycle, finishes and building envelope (in particular, insulation and moisture protection) are the most significant items, accounting for about 60 percent and 20 percent respectively of the recurring embodied energy (which are similar in proportion to those in Hong Kong).
3.2.3 Observations

The quantitative assessment and comparison on a per capita basis reveal the following key characteristics about the recurring embodied energy of Hong Kong's high-density housing:

- OCCUPANCY DENSITY & INTERIOR COMPONENTS

  The interior components represent the predominant factor in the above assessment. The occupancy density (the ratio between interior floorspace and occupant) thus particularly has considerable effects on the magnitude of recurring embodied energy: the less living space available per person, the less the probable recurring embodied energy required per capita.

- BUILDING DENSITY & EXTERIOR COMPONENTS

  The correlation between recurring embodied energy and building density (and residential density) is less apparent. Although a tall building commonly causes the periodic maintenance, especially its building envelope, to be resource-intensive since extensive temporary works and hoisting equipment are required to support the working processes at high levels above ground, the frequency and extent of maintenance for the building envelope can be minimized through an appropriate choice of durable finishing materials and assemblies. In practice, instead of paint or stucco finishes for the external wall of low-rise dwellings which require relatively frequent maintenance, more durable alternatives such as ceramic tiles fixed with adhesive or fair-faced concrete finishes are preferably specified for the building envelope of high-rise apartments in order to reduce the level of recurring embodied energy.

The estimate of recurring embodied energy is intended to reflect the approximate orders of magnitude for the purpose of comparison between the selected dwelling archetypes and between the categories of energy use. In addition to the physical parameters (such as floorspace per occupant and building height), the recurring embodied energy of a building which emphasizes the household interiors is inevitably subject to the influence of occupants socio-economic characters. Further research is hence necessary to make the relationship between dwelling densification and recurring embodied energy more conclusive.
3.3 OPERATING ENERGY

3.3.1 Overview

The categories of space conditioning (heating, cooling, etc.), lighting, and clothes drying are those household operations most influenced by architectural design (Stein and Reynolds, 1992). On the other hand, the operating energy consumption related to the use of many other household appliances such as washing machine and water heater largely depends upon the lifestyle of occupants and the energy efficiency of appliances. In this study, the focus is thus put on the former, i.e., those aspects of operating energy dependent on the spatial and physical design of dwellings. The household operating energy use which includes space conditioning, electric lighting, clothes drying and communal services is to be discussed in the following sections.

The usage of other household appliances constitutes a significant sector of energy consumption in an industrialized society where more household practices become energy-dependent. For instance, as shown in Table 3.2, the annual energy used for household appliances (i.e., those usages which are largely independent of the architectural design) is estimated at about 10 GJ per person for an average household in both Hong Kong and North America. In this study, the usage of household appliance which is considered largely independent of the building design includes water heating, cooking, clothes washing, entertainment, use of home computer, etc. Considerable energy reductions for these usage are possible independent of the physical characteristics of the building, but through environmental education and technological improvements. Therefore, this category of operating energy use is distinguished and excluded from the scope of assessment in this study.

3.3.2 Density-Dependent Operations

Table 3.2 shows the typical domestic operating energy consumption in Hong Kong and North America. The annual operating energy related to space conditioning, lighting, clothes drying, and communal services are separately categorized.
### TABLE 3.2 COMPARISON OF OPERATING ENERGY CONSUMPTION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE PER CAPITA ENERGY CONSUMPTION (MJ per person per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>HONG KONG</strong></td>
</tr>
<tr>
<td></td>
<td>Dwelling Archetype:</td>
</tr>
<tr>
<td></td>
<td>HIGH-DENSITY MULTIPLE-</td>
</tr>
<tr>
<td></td>
<td>FAMILY APARTMENT</td>
</tr>
<tr>
<td>Space Conditioning</td>
<td>4,000 27%</td>
</tr>
<tr>
<td>Electric Lighting</td>
<td>500 3%</td>
</tr>
<tr>
<td>Clothes Drying</td>
<td>500 3%</td>
</tr>
<tr>
<td>Communal Services</td>
<td>1,000 7%</td>
</tr>
<tr>
<td><strong>SUB-TOTAL:</strong></td>
<td>6,000 40%</td>
</tr>
<tr>
<td>Water Heating</td>
<td>4,000 27%</td>
</tr>
<tr>
<td>Other Appliances</td>
<td>5,000 33%</td>
</tr>
<tr>
<td><strong>SUB-TOTAL:</strong></td>
<td>9,000 60%</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td>15,000 (or 15 GJ/person/year)</td>
</tr>
</tbody>
</table>

SPACE CONDITIONING

Table 3.2 shows that space conditioning (cooling and/or heating) is the dominant aspect of operating energy that is very much dependent on building design. Space conditioning accounts for about 4 and 35 GJ per person per year in the typical household in Hong Kong and North America respectively. While the energy use for thermal comfort undoubtedly correlates with local climate, the physical design of dwellings has a major role in influencing the magnitude of operating energy for mechanical space conditioning.

The climate in Hong Kong is relatively mild as compared with many of the North American cities, especially those in the higher latitudes and with long, cold winters. Therefore, instead of having a direct comparison between the operating energy of domestic space conditioning in Hong Kong and North American cities, this study focuses on an examination of the usage pattern of mechanical space conditioning in Hong Kong's apartment buildings.

Hong Kong has a humid sub-tropical climate. Mechanical space conditioning thus almost equates to air-conditioning (mechanical space cooling) for dwellings in this climate. In the 1970s, its population adapted to this climate without much reliance on energy-intensive means of cooling; electrical fans were used occasionally in some extremely hot humid days in the summer. Recognizing that a certain period in its summer is particularly humid and hot and the expected levels of thermal comfort have been increased considerably, a recent research on Hong Kong's annual weather pattern has shown that theoretically only about one-third of the current domestic usage of air-conditioning is considered "essential" (ERM, 1993). The research implies that the other two-thirds of operating energy currently used for space conditioning (i.e., about 2 to 3 GJ/person/year) could be possibly saved while maintaining a reasonable level of thermal comfort, provided that the architectural design offers an appropriate means of passive cooling (especially natural ventilation cooling) and the urban micro-climate does not deteriorate notably.
Natural ventilation cooling is most appropriate in humid, hot climates where temperatures are only slightly lower by night than by day. Through this strategy, a building should be very open to breezes while simultaneously closed to direct sun; and higher air temperatures can hence be offset by increased air motion. Architecturally, this cooling strategy relies on rather narrow plans with large ventilation openings on either side (Stein and Reynolds, 1992). How well is the prevalent form of high-density housing in Hong Kong adapted to this cooling strategy? In term of the layout of dwelling units, the common cruciform plan with eight households per floor is not particularly effective in capturing the prevailing breeze. In term of the layout of building towers, neighbouring towers (and adjacent developments in a compact urban area) of similar building height often result in an inter-block effect reducing the overall exposure of most dwelling units to prevailing breeze.

• ELECTRIC LIGHTING

As shown in Table 3.2, electric lighting accounts for about 0.5 and 1 GJ/person/year in the typical household in Hong Kong and North America respectively. The use of electric lighting is commonly considered dependent on the characteristics of building design. The difference in floorspace per occupant evidently has a role in contributing to the difference in energy consumption for space illumination.

However, in Hong Kong where the living space of a dwelling unit is typically modest in size and less than 6 metres from a window, further energy reductions through improvement in daylighting provision will be modest. For the detached single-family dwellings, daylighting provision is also frequently possible for most daytime activities at home, provided that the architectural design has taken the advantage of the high ratio between building envelope and floorspace. From this perspective, the difference in dwelling densities (and in building typology) is not a significant factor refraining architectural design from the option of daylighting use.
CLOTHES DRYING

Clothes dry is an example of the shift from passive to active means of household practice in the contemporary society. As shown in Table 3.2, the operating energy for mechanical clothes drying accounts for about 0.5 GJ/person/year in the typical household in both Hong Kong and North America. Despite the similarity in their energy consumption in this regard, there are differences in terms of the causes and the possibility to change. In Hong Kong's high-rise apartments, the effectiveness of passive drying option is largely constrained by building design. However, in North American single-family dwellings, the option of using clothesline always remains open.

In Hong Kong, the traditional practice of clothes drying is to utilize the availability of ambient energy, i.e., the solar and wind energy -- which are relatively abundant throughout the year. However, the current form of *point block* towers only provides limited hanging space in their "reentrant" where the harness of ambient energy for clothes drying is usually not very effective. The vertical staggering of clothes hanging space in a high-rise apartment building also causes further constraints to the effectiveness of passive drying. The current shift to using mechanical clothes dryer is thus encouraged.

In a detached single-family dwelling with private open space, however, the possibility of using outdoor clothesline with convenience and effectiveness is evidently without much physical and spatial constraints. There has been a social trend from labour-intensive to energy-intensive practice of clothes drying in North America, though. The use of the energy-intensive mechanical clothes dryer was increasing in the United States; according to Stein and Reynolds (1992), energy consumption for this purpose increased by about 10 percent per year in the 1970s. Nonetheless, the option of using outdoor clothesline remains available in the single-family dwellings.
• COMMUNAL SERVICES

Table 3.2 shows that the operating energy associated with communal services is approximately 1 GJ/person/year in Hong Kong's high-rise apartment buildings. In the apartment buildings, there are typically a variety of shared facilities that require energy for their daily operation. Examples include lights and security systems for common areas, pumps for fresh and flushing water supply, and exhaust fans and the other operations for communal mechanical areas.

(In this thesis, the operating energy related to conveyance systems such as passenger lifts in multi-storey buildings is discussed in Section 3.5.)

3.3.3 Observations

In sum, the quantitative assessment and comparison made on a per capita basis reveal the following key characteristics about the operating energy of Hong Kong's high-density housing archetype:

• OCCUPANCY DENSITY & INTERIOR SPACE-DEPENDENT OPERATIONS

Some of the categories of energy consumption are proportional to the size of dwelling space, i.e., the more space per occupant, the more energy consumed for the operations. Space conditioning and electric lighting are the two major examples. For instance, it is evident if the occupancy density in North American cities were reduced to a level similar to that in Hong Kong, its operating energy consumption for space conditioning would be very much lowered despite the other differences such as the apparently large climatic variation.

From this viewpoint, the high occupancy density in Hong Kong is a "positive" contributing factor to its relatively low operating energy consumption, particularly for mechanical space conditioning which is potentially a very energy-intensive component of the domestic building operation.
HIGH-RISE & INCREASING DEPENDENCE ON MECHANIZATION

The high-rise form of dwelling in Hong Kong physically entails a number of constraints on the daily living pattern of occupants. It limits the possibility of harnessing ambient wind for natural ventilation cooling, and induces an increasing dependence on mechanical air-conditioning. It constrains the effectiveness of drying clothes outdoors, and induces an increasing dependence on mechanical clothes dryers. It requires "additional" energy for pumping potable and flushing water for household usage in upper storeys. Considering the magnitude of energy consumption and the probable magnitude of energy savings, space conditioning is clearly the prime concern in this regard.

In Hong Kong, the process of dwelling densification (particularly in terms of high building densities and residential densities) has a close correlation with the shift to an increasing use of air-conditioner. The decentralized (or local) air-conditioning system is common for the high-rise apartment buildings. Individual households install their own window-mount air-conditioner(s) which is flexible in terms of operation and maintenance. However, as described by Stein and Reynolds (1992), the drawback of the local systems is that noise and other by-products [such as waste heat] of multiple machines pose numerous potential threats to occupied spaces. The local noise and heat pollution trapped around dwelling units commonly worsen the quality of the micro-environment, and in turn induce more occupants to use their air-conditioner more frequently. Such a chain effect increasingly causes the individual option of using passive means of cooling to become less favourable, especially in the urban areas of high building and residential densities.

Overall, in Hong Kong, while higher occupancy densities are conducive to lower per capita energy consumption for space conditioning, high building and residential densities constrains the probable extent of harnessing the renewable ambient energy for space cooling in most households.
3.4 COMMUTING ENERGY

3.4.1 Overview

In cities, residential density has profound implications on the overall urban density, which in turn has a close correlation with the average per capita energy consumption for passenger transportation. People travel between home and workplace, shop and other facilities for leisure, education, etc. While recognizing the socio-economic, cultural and climatic variables, it is evident that the physical characteristics of residential area (including primarily its population densities and other parameters like mixture of land use, etc.) are the prime factors influencing the prevalent mode(s) of transportation, the distances of travel, and hence the energy efficiency of passenger commuting pattern (Breheny et al., 1993; Newman and Kenworthy, 1989).

In a typical spread city like many of those in North America, the prevalent commuting pattern is primarily "horizontal" and automobile-dependent. In a compact city like Hong Kong, the commuting pattern basically comprises both "horizontal" and "vertical" movements; in addition to the traffic on road and rail, people frequently travel by vertical conveyance systems such as lifts and escalators. In addition to a "horizontal mixture" of land use as fostered through the process of dwelling densification, Hong Kong as coined to be a "vertical city" offers many opportunities for a "vertical mixture" (or staggering) of land use. People can thus commonly travel between home at upper levels and a variety of neighbourhood facilities such as shop, market, kindergarten, playground, etc. at lower levels by lift and on foot -- which is conceptually equivalent to the use of vehicles for a similar purpose in a city with sprawling suburbs.

In view of the above, this study includes the operating energy consumption related to both the "horizontal" and "vertical" passenger movement systems in this section titled "commuting energy". Commuting energy, which is a significant sector of energy consumption in cities, has a very close correlation with the issue of densification.
3.4.2 Horizontal & Vertical Systems

In *Cities and Automobile Dependence*, Newman and Kenworthy (1989) studies the urban form, transport and energy use in thirty-two international cities from North America, Europe, Asia and Australia. The identified correlation between gasoline use per capita and urban density is shown in Figure 3.1. The comparative data has been adjusted to U.S. income, vehicle efficiencies and gasoline prices. Among the cities examined, Hong Kong having the highest urban (and residential) density scores the lowest per capita gasoline consumption: about 5 to 5.5 GJ per person per year. North American cities are associated with the highest range of per capita gasoline consumption: about 50 to 70 GJ per person per year. The difference in the per capita gasoline consumption is significant between Hong Kong and North American cities. (To add, according to Breheny et al. [1993], the population size also has a key role in influencing gasoline consumption. In the U.K., a travel survey has demonstrated that its largest and most dense city, London, is not the most efficient when compared with other smaller towns of certain size.)

On the other hand, for the typical residential towers in Hong Kong, the recurring energy use associated with vertical conveyance system varies with building height, service performance (including the number, traveling speed and capacity of lift), and system efficiency etc. The annual energy consumption is estimated at the order of 0.5 to 1 GJ per occupant (see Table 3.2). In sum, the corresponding per capita commuting energy on average is approximately 6 and 60 GJ per person per year for Hong Kong's high-density housing and North American low-density dwelling respectively, i.e., in a ratio of about 1 to 10.

3.4.3 Observations

As pointed out by Newman and Kenworthy (1989), the difference in passenger commuting energy consumption has a close correlation with the difference in urban density [which is in turn very much dependent on residential density]. The following observations can be further elaborated with respect to the characteristics of dwelling densification in Hong Kong:
FIGURE 3.1 GASOLINE USE PER CAPITA VERSUS URBAN DENSITY ADJUSTED TO U.S. PARAMETERS, 1980
• RESIDENTIAL DENSITY & GASOLINE CONSUMPTION

The current level of dwelling densification (high residential density as a collective effect of high occupancy density and building density) in Hong Kong evidently leads to a very low level of gasoline use per capita (one-tenth and even less of that in North American cities). As indicated in Figure 3.1 which shows the projected relationship between gasoline use per capita and urban density, there are two other noteworthy points about the theoretical effects due to adjustments of residential density in Hong Kong. Firstly, if the current level of urban density (or residential density) in Hong Kong were reduced by one-third or even half, there would only involve very slight changes in the per capita gasoline consumption. Secondly, further densification in Hong Kong would only have minimal gains in the conservation of commuting energy as a result of diminishing return.

• BUILDING DENSITY & VERTICAL MOVEMENT SYSTEM

Although increasing building densities often leads to high-rise buildings and entails the requirement of a vertical passenger movement system, the "additional" energy use of vertical conveyance is generally offset by the savings in the gasoline consumption of automobile and other transportation systems. In dense urban areas, the vertical conveyance system is potentially an energy efficient and environmentally sensitive (e.g., less local noise, heat and air pollutions) alternative for people movement as opposed to the vehicular system. In Hong Kong, the vertical conveyance system is currently utilized not only in individual high-rise buildings, but also on a larger urban scale where pedestrians can travel comfortably between urban blocks located at different datum. An example of this urban conveyance system comprising a network of covered escalators, footbridges and walkways is located across the Central District and Mid-Levels of Hong Kong Island. Instead of relying on car or bus, people living in Mid-Levels can travel from their dwelling unit by lift to the street level and then by the outdoor escalators to workplaces and shops located densely around the conveyance network.
3.5 DEMOLITION ENERGY

3.5.1 Overview

Energy is used to demolish buildings and transport and dispose of "waste" material. Current demolition practice commonly involves intense application of energy and haulage to landfill or dumping sites. The prime difficulty assessing demolition energy is predicting future demolition practices some 50 years later or more. At that time, it is reasonable to anticipate that the salvaging of materials will assume greater importance and that greater effort and time will be expended in removal, sorting and cleaning materials for reuse or return to the material industries for recycling.

3.5.2 Estimation

Published figures on the actual amount of energy associated with the demolition and attendant transportation of recyclable materials and debris are limited. The US Advisory Council on Historic Preservation suggests 136.2 MJ per square metre for the demolition of a 5,000 square metre concrete building. Quantitatively, these figures represent approximately 1 to 3 percent of the initial embodied energy of the building (Cole and Wong, 1996). Given that the initial embodied energy of the dwelling archetype in Hong Kong and North America is respectively 1.5 to 2 GJ/person/year and 3 to 6 GJ/person/year over a notional building lifetime of 50 years (see Section 3.1), the corresponding demolition energy averaged on an annual basis is thus estimated at 20 to 50 MJ/person/year and 30 to 150 MJ/person/year respectively.

3.5.3 Observation

The published information regarding the detail of building demolition is very limited. More research is recommendable, especially regarding the demolition of high-rise structure in tight construction sites which require more safety measures and labour-intensive approaches. As the efficiency of other energy use improves, demolition energy represents an increasing component of total energy. Nonetheless, from the viewpoint of life-cycle energy use, the current demolition energy of a building is estimated at less than one percent of the overall energy consumption (see Table 3.3). Demolition energy is considered relatively insignificant in this study.
3.6 SUMMARY

3.6.1 Life-Cycle Energy Use

The life-cycle energy use is derived by the summation of the five components of energy consumption: initial and recurring embodied energy, operating energy, commuting energy, and demolition energy. Table 3.3 shows the life-cycle energy use related to the selected dwelling archetype in Hong Kong and North American cities over a 50 year building lifetime. The difference in the overall per capita energy consumption (i.e., 15 GJ per person per year in Hong Kong versus 100 GJ per person per year in North America) is substantial.

Such significant difference is largely attributed to the usage pattern of commuting energy and operating energy. Initial (and recurring) embodied energy has an increasing significance, in case there are high efficiencies and/or improvements in the operating and commuting energy use. In particular, the significance of initial embodied energy also increases in case of short effective life-span of a building. The following sections thus further examine and summarize the implications of Hong Kong's dwelling densification with emphasis on the three key components of energy use:

- COMMUTING ENERGY,
- OPERATING ENERGY, and
- INITIAL EMBODIED ENERGY.

3.6.2 Commuting Energy

Commuting energy is by far the largest component of energy consumption, representing approximately 40 percent and 58 percent of the life-cycle energy use in the dwelling archetype in Hong Kong and North America respectively. Quantitatively, however, the difference in energy use (i.e., 5.5 to 6.5 GJ per person per year in Hong Kong versus 50 to 70 GJ per person per year in North America) is remarkable. Such a difference in magnitude overrides the effects of many other energy components.
TABLE 3.3  COMPARISON OF PER CAPITA ENERGY CONSUMPTION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE PER CAPITA ENERGY CONSUMPTION (MJ per person per year)</th>
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<tbody>
<tr>
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<tr>
<td></td>
<td>Dwelling Archetype:</td>
</tr>
<tr>
<td></td>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
</tr>
<tr>
<td></td>
<td>(building life-span = 50 years)</td>
</tr>
<tr>
<td>Initial Embodied</td>
<td>1,500 - 2,000</td>
</tr>
<tr>
<td>Energy</td>
<td>12%</td>
</tr>
<tr>
<td>Recurring Embodied</td>
<td>1,000 - 1,500</td>
</tr>
<tr>
<td>Energy</td>
<td>8%</td>
</tr>
<tr>
<td>Operating Energy</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>Commuting Energy</td>
<td>5,500 - 6,500</td>
</tr>
<tr>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>Demolition Energy</td>
<td>20 - 50</td>
</tr>
<tr>
<td></td>
<td>less than 1%</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>14,020 - 16,050</td>
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<tr>
<td></td>
<td>(say, 15 GJ/person/year)</td>
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</tbody>
</table>
Even if technological improvements could reduce the level of gasoline consumption of private automobile by half in the future and the average traveling distance were maintained in the current level, the difference in commuting energy between Hong Kong (a compact city with high dependence on mass transit, pedestrianization and vertical conveyance system) and North American cities (those spread cities with high dependence on private automobile) would still represent a dominant position of life-cycle energy use.

From the perspective of reducing per capita energy consumption, dwelling densification as that in Hong Kong (through the collective effect of high occupancy density, building density and residential density) is thus highly "positive", since it is effectively conducive to suppressing the biggest probable sector of energy use, i.e., commuting energy.

3.6.3 Operating Energy

Operating energy is the second largest component of energy use, representing approximately 40 percent and 36 percent of the life-cycle energy use in the dwelling archetype in Hong Kong and North American cities respectively. Quantitatively, the difference in energy use (i.e., approximately 6 GJ per person per year in Hong Kong versus 36.5 GJ per person per year in North American cities) is significant. (In this Section, the discussion of operating energy is confined to those largely and directly dependent on the physical and spatial characteristics of buildings, such as space conditioning, electric lighting, clothes drying, and communal services [e.g., electric lighting and mechanical ventilation for common areas, etc.])

As briefly discussed in Section 3.3, increasing occupancy densities can be conducive to reducing the levels of operating energy, while very high building densities as those prevalent in Hong Kong can entail "negative" effects on the conservation of energy in building operations. In view of the opposite effects of occupancy density and building density as identified in this study, the overall implication of residential density on operating energy use is hence less conclusive.
• OCCUPANCY DENSITY

Space conditioning typically accounts for the largest sector of energy consumption among this category of operating energy. Climatic variation is thus often taken as the reason to explain the difference in operating energy. While recognizing the probable effects of climate as discussed in Section 3.3.3, the large difference in occupancy density is evidently an equally significant parameter which magnifies the ultimate difference in the energy consumption of mechanical space conditioning.

Therefore, in the case where it is inevitable to use mechanical means of space conditioning fueled by non-renewable energy sources, high occupancy density as that in Hong Kong is considered "positive" from the viewpoint of energy conservation. High occupancy density, i.e., less floorspace per person, induces a reduced scale of proportion in the energy use.

• BUILDING DENSITY

As a result of the high building densities and the short-term economic priority in most property development, the current prevalent form and layout of point block residential towers frequently constrain the harness of ambient energy (wind and/or solar energy) for natural ventilation cooling as well as clothes drying in individual flats.

However, this deserves the further attention of designers since there is significant scope for improvements through more environmentally-responsive planning and design. The probable energy savings could be in the order of approximately 3 GJ per person per year through minimizing the energy use associated with the "non-essential" mechanical space cooling and clothes drying as discussed in Section 3.3.2. Such magnitude of energy conservation can be significant, representing the possibility of 50 percent reduction in the operating energy use and in turn a 20 percent reduction in the overall per capita energy consumption (i.e., a shift from 15 to 12 GJ per person per year).
3.6.4 Initial Embodied Energy

Initial embodied energy is the third largest component of energy consumption, representing approximately 12 percent and 4 percent of the life-cycle energy use in the dwelling archetype in Hong Kong and North America respectively. Quantitatively, however, the difference in energy use (i.e., 1.5 to 2 GJ per person per year in Hong Kong versus 3 to 6 GJ per person per year in North America) is comparatively modest, but still deserves attention.

The above figures are derived from the notion that an effective lifetime of a building is about 50 years. However, for instance, for a 25 year life-span of the building, the initial embodied energy of Hong Kong’s typical point block residential tower would be doubled on the per person-year basis, amounting to approximately 3 to 4 GJ per person per year (Cole and Wong, 1996). This would hence represent about 20 percent of the overall life-cycle energy use.

The comparison of initial embodied energy between the dwelling archetype of Hong Kong and North American cities reveals its close dependence on occupancy density and building density. The relationship between initial embodied energy and residential density is indirect and less apparent, since it is subject to the opposite effects of occupancy density and building density. As discussed in Section 3.1.3, increasing occupancy density is conducive to lowering per capita initial embodied energy whereas very high building densities as those prevalent in Hong Kong lead to high levels of initial embodied energy per unit floor area. Overall, in contrast to the typical single-family dwellings in North America with very low occupancy rate, Hong Kong’s prevalent form of high-density housing shows a lower level of per capita initial embodied energy (which is about half to one-third of that in North America).

However, if the occupancy density continues to decrease in Hong Kong (through both decreasing number of persons by home and increasing home size) as mentioned in Section 1.2.4, the apparent "positive" effect of high residential density on initial embodied energy will diminish.
3.6.5 Conclusions

Figure 3.2 summarizes the relationships between dwelling densification and energy use in a graphic form. The "hierarchy of significance" shows the relative importance of the five categories of energy use according to their magnitude of per capita energy consumption in the life-cycle analysis. Commuting energy, operating energy, and initial embodied energy are the three most significant components, whereas demolition energy is relatively insignificant. The relevance to "density-dependence" is addressed on the different scales of reference, i.e., in terms of occupancy density, building density, and residential density. The "+" or "+" mark represents a component of energy use which indicates high relevance to density dependence, but the relationship can be either "positive" or "negative" in effect with respect to the concern of reducing per capita resource consumption. The "shaded" cells represent those whose density dependence is low or ambiguous.

The following key relationships between dwelling densification and energy use are identified:

- **OCCUPANCY DENSITY**

  High occupancy density is conducive to low levels of per capita energy consumption. Its implication on commuting energy is indirectly made through its effect on residential density: the higher the occupancy density, the higher the residential density. Its "positive" implications on operating energy, initial embodied energy and recurring embodied energy are largely based on an economy of proportion: "less is more". Since mechanical space conditioning is the key component of operating energy, more conservative standards of per capita floorspace has a direct effect on reducing the ultimate volume of interior space requiring heating or cooling and in turn reducing the operating energy use in proportion. The effect of occupancy density on the energy use for space conditioning, however, will diminish if there is appropriate compartmentation design for individual dwelling units (for instance, the living space is divided into a number small units and the space conditioning system is designed with zoning control).
<table>
<thead>
<tr>
<th>ENERGY USE</th>
<th>DENSITY-DEPENDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CATEGORY OF USAGE</strong></td>
<td><strong>HIERARCHY OF SIGNIFICANCE</strong></td>
</tr>
<tr>
<td>Initial Embodied Energy</td>
<td>3</td>
</tr>
<tr>
<td>Recurring Embodied Energy</td>
<td>4</td>
</tr>
<tr>
<td>Operating Energy</td>
<td>2</td>
</tr>
<tr>
<td>Commuting Energy</td>
<td>1</td>
</tr>
<tr>
<td>Demolition Energy</td>
<td>5</td>
</tr>
<tr>
<td><strong>LIFE-CYCLE ENERGY USE :</strong></td>
<td>+</td>
</tr>
</tbody>
</table>

**FIGURE 3.2**  MATRIX OF RELATIONSHIP BETWEEN DWELLING DENSIFICATION AND ENERGY USE
• BUILDING DENSITY
In contrast to occupancy density, the "merits" of high building densities as those prevalent in
Hong Kong are less certain. On one hand, the "positive" implication on commuting energy is
indirectly made through the effect on residential density: the higher the building density, the
higher the residential density. On the other hand, high building densities (say, in term of plot
ratio 5 and above) can lead to "negative" effects on both operating energy and initial
embodied energy. Through the constraints on architectural design, high building densities
frequently constrain the harness of available ambient energy for utilization, and foster an
increasing reliance on mechanical means of household operations. The resultant height of
buildings (30 to 40 storeys) also entails the use of energy intensive materials for construction
and leads to high initial embodied energy per unit floor area.

• RESIDENTIAL DENSITY
In Hong Kong, as the effect of high occupancy densities overrides that of high building
densities, the high residential densities are conducive to low levels of initial embodied energy
of buildings on a per capita basis. On the other hand, from an environmental viewpoint that
places emphasis on optimizing planning and design of housing to harness renewable energy,
the high residential densities as a consequence of very high building densities are considered
to have a "negative" relationship with respect to the use of operating energy. In comparison
with the other industrialized cities, however, Hong Kong's high residential densities (in
conjunction with appropriate mixed land use and public transportation infrastructure and
management) positively contribute to a very significant reduction in the per capita gasoline
use. Such energy savings outweighs the probable "negative" effect of other components of
energy use. Overall, in Hong Kong, the high residential densities are thus conducive to low
levels of per capita energy use.
CHAPTER IV  
WATER-DENSITY RELATIONSHIP

4.1 OVERVIEW

4.1.1 Approaches & Quantification

As set out in Section 2.1.3, there are two key objectives in the discussion of domestic water use: (1) to conserve water resource, in particular potable water, and (2) to use on-site "wastewater" which is considered a resource. These two environmental concerns are closely interconnected.

Broadly speaking, the conservation of potable water is achievable by two fundamental approaches: (1) reduction, and (2) substitution. For instance, the amount of potable water use for irrigation can be reduced through xeriscape design; alternatively, treated greywater or harvested rainwater, instead of high-quality potable water, can be utilized for watering purpose. However, household wastewater (including greywater and blackwater) and rainwater are commonly conceived as "waste" and disposed of. From an environmental perspective, the beneficial use of these "underutilized" resources available on-site has two main implications: firstly, to reclaim the useful nutrients contained particularly in the household wastewater; secondly, to substitute potable water for non-potable use such as irrigation and toilet flushing.

Table 4.1 compares the amounts of domestic water consumption and on-site "wastewater" availability on a per capita basis between Hong Kong's high-density housing archetype and a typical North American single-family dwelling. On average, the daily domestic water consumption is estimated at approximately 220 and 450 litres per person respectively. The daily quantity of household wastewater plus rainwater harvestable on-site is approximately 210 and 350 litres per person respectively. (The figures are simplified, in particular with respect to the seasonal effects on water demand, especially irrigation water use, and rainwater availability. Nonetheless, the use of these average figures is considered sufficient for the purpose of an initial assessment.)
### Table 4.1: Comparison of Per Capita Water Usage Pattern Between Hong Kong's High-Density Housing and North American Single-Family Dwelling

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE PER CAPITA QUANTITY (litre per person per day)</th>
<th>HONG KONG</th>
<th>NORTH AMERICAN CITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dwelling Archetype: HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td>Reference Model: LOW-DENSITY SINGLE-FAMILY DETACHED HOUSE</td>
</tr>
<tr>
<td>Potable Water Use</td>
<td></td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68 %</td>
<td>30-40 %</td>
</tr>
<tr>
<td>Flushing Water Use</td>
<td></td>
<td>65</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 %</td>
<td>20-30 %</td>
</tr>
<tr>
<td>Irrigation Water Use</td>
<td></td>
<td>5 - 10</td>
<td>varies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 %</td>
<td>(100 - 270)</td>
</tr>
<tr>
<td></td>
<td>TOTAL: (Domestic Water Consumption)</td>
<td>220 - 225</td>
<td>370 - 540</td>
</tr>
<tr>
<td></td>
<td>(say, 220 litre/person/day)</td>
<td></td>
<td>(say, 450 litre/person/day)</td>
</tr>
<tr>
<td>Wastewater Generation</td>
<td></td>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95 %</td>
<td>60-80 %</td>
</tr>
<tr>
<td>Rainwater Availability</td>
<td></td>
<td>5 - 10</td>
<td>varies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 %</td>
<td>(50 - 150)</td>
</tr>
<tr>
<td></td>
<td>TOTAL: (Alternative Water Sources On-Site)</td>
<td>205 - 210</td>
<td>300 - 400</td>
</tr>
<tr>
<td></td>
<td>(say, 210 litre/person/day)</td>
<td></td>
<td>(say, 350 litre/person/day)</td>
</tr>
</tbody>
</table>

4.1.2 Conservation of Potable Water

With respect to the use of water, a fundamental environmental concern taken in this study is to reduce per capita consumption of \textit{potable water}. For instance, Hong Kong currently relies on the importation of about 70 percent of its annual potable water demand from Pearl River Delta in Mainland China (Yeung, 1992). However, since the water demand in Pearl River Delta is increasing rapidly as a result of expanding urbanization, population growth, there are increasing warnings that the cities in Pearl River Delta, including Hong Kong, would face a "water crisis" by the Year 2003 (Shenzhen Warns of Water Shortage, 1996). In addition to the search for new sources of water supply at distances, demand-side water conservation evidently has a major role in addressing water shortage. As the global population increases, potable water is becoming a more scarce resource. Water conservation is an increasingly important urban issue.

To reduce the demand for potable water, an approach is to differentiate the domestic water usages according to their different requirement of water quality. In the contemporary society, the use of water for domestic operations can be distinguished into three main components:

- potable water use (i.e., potable water used indoors for drinking and cooking, bathing and personal hygiene, laundry and dishes washing, other cleansing, etc.),
- flushing water use, and
- irrigation water use.

Both flushing and irrigation water use do not require high-grade potable water. If alternative water source is supplied for these two usages, the domestic demand for potable water can be reduced by 30 to 70 percent according to a preliminary estimate based on the figures in Table 4.1. From this viewpoint, the potential savings of potable water can be very significant. Table 4.1 also shows that the amount of "alternative" water sources available on-site can potentially match the requirement of both flushing water and irrigation water use. Section 4.1.3 further elaborates the utilization of on-site wastewater and rainwater.
4.1.3 Use of Alternative Water Source On-Site

This section is concerned with domestic "wastewater" (including greywater and blackwater) and rainwater. Household wastewater refers to the effluent from sinks, basins, baths, and toilets. Rainwater can be collected from a roof (or other catchment area). In urban areas, however, both of them are commonly considered a liability, and disposed of via sewers and drains.

Tjallingii (1995) contends, "[wastewater] problems have been 'solved' in the past by increasing supply and discharge and by rinsing through. As a result the problems in the supply and discharge areas increases. The problems are passed on." (p. 10). The fundamental environmental concerns taken in the thesis are hence in twofold. First, appropriately treated domestic wastewater is considered a water source for "low-grade" tasks, so that the demand for potable water can be ameliorated. Second, domestic wastewater is a nutrient-rich resource; closing the nutrient cycles is crucial from an environmental perspective. Brown (1992) predicts, "the viability of agriculture -- and, by extension, cities may hinge on how successfully urban areas can recycle this immense volume of nutrients [discharged from households]." (p. 7). In view of the above, sophisticated and extensive central sewage treatment systems accompanied by "telescopic" discharge pipes linking to distant sea bed may only mitigate the level of local water pollution, but in effect pass on the environmental problems. On one hand, the vital resource for nutrient cycles is under depletion. On the other, the assimilative capacity of aquatic ecosystem, the "sink", is put under increasing stress. Therefore, an emerging challenge for cities is to restore a cyclic relationship between "water input" and "wastewater output", in order to optimize the efficiency in the use of water resource and the reclamation of nutrient resources (Girardet, 1992; Stein and Reynolds, 1992).

On the other hand, as suggested by Pacey and Cullis (1986), collecting and using precipitation from a roof or other catchment area is an excellent way to take advantage of natural site resources, to reduce site runoff and the need for runoff control devices, and to minimize the need for utility-provided water. However, the effectiveness of rainwater harvesting varies with population density.
4.2 COMPONENTS OF WATER USE & RELATED ISSUE

4.2.1 Potable Water Use

As shown in Table 3.1, indoor potable water use is the largest category of the typical household water consumption in both Hong Kong and North American cities, representing approximately 150 litres per person per day on average in each case. The probable effect of physical and spatial characteristics of dwelling units on indoor potable water use is not evident. The amount of indoor water usage largely depends on the lifestyle of occupants and the efficiency of household appliances and fixtures, i.e., whether the occupants bath or use shower; and whether a conventional or "water saving" shower head is used, etc. As estimated by Stein and Reynolds (1992), an approximate 25 percent reduction in the indoor usage of water is achievable through simple conservation measures such as flow controls. The corresponding daily water consumption would be about 110 litres per person.

This study excludes the option of reclaiming on-site rainwater and other domestic wastewater for potable use (such as drinking, cooking, bathing, laundry, etc.), in view of the stringent expectation of water quality for human nourishment and hygiene in cities. In particular, increasing urban pollution and "acid rain" threaten the quality of rainwater in urban areas, causing the use of rainwater collected on-site less suitable for indoor usage directly or after simple treatment.

4.2.2 Flushing Water Use

Flushing water use represents approximately 20 to 30 percent of the domestic water use in the dwelling archetype in both Hong Kong and North American cities, accounting for about 65 and 120 litres per person per day respectively. The difference in the amount of flushing water consumption is largely attributed to the flushing mechanism of toilets. In Hong Kong the volume of water use per flush is typically designed between 9 and 15 litres, whereas in the cities of Canada and the United States the corresponding water volume per flush is commonly between 13 and 26 litres for the conventional toilets (Stein and Reynolds, 1992; Vale, 1991).
Nonetheless, flushing water use is a significant category of water use with scope for reductions. Technologically, the innovations in low flush toilet (or "watersaver toilets") can reduce the required amount of water per flush. Alternatively, instead of using "high-grade" potable water for flushing -- which is currently a normal practice in most industrialized cities -- "low-grade" water can be utilized for flushing purpose. As criticized by Stein and Reynolds (1992), there is perhaps no more flagrant example of a mismatch in building design than the high-grade resource of potable water being used for the low-grade task of flushing. Rainwater harvesting is a potential opportunity for providing an on-site source of low-grade water supply for flushing use. In Hong Kong, a harbour city, sea water in lieu of potable water is utilized for toilet flushing in most of its territory.

Hong Kong is one of only a very few places in the world which have been successful in supplying sea water to replace potable water for flushing purpose. When Hong Kong introduced sea water for flushing in the late 1950s, it was in fact a pioneer move in view of the then acute shortage of water for potable use. Since the 1950s and 1960s, Hong Kong has been renown for its high population densities. As stimulated by the acuteness of water scarcity and facilitated by the compactness of urban settlements, Hong Kong has taken the opportunity of developing sea water flushing system for use on a municipal scale.

According to the recent programme of Hong Kong's Water Supplies Department, the percentage of sea water usage will be approximately 90 percent of its total population by 1997 (HK-WSD, 1995). The remaining 10 percent population lies outside the already planned sea water flushing supply zone, since it is presently uneconomical to provide sea water to these areas for flushing on account of the following reasons: (1) their remoteness from suitable source of sea water (e.g., Yuen Long, Sheung Shui and Fanling in the north and north-west New Territories), (2) small population (such as in outlying islands), or (3) low population densities (the peak and south in Hong Kong Island, and Sai Kung in the east New Territories).
In light of the experience in Hong Kong, the success of reducing potable water demand through the use of marine water for flushing is dependent on two main enabling factors: firstly, the proximity to an appropriate source of sea water (for example, too much silt contents of marine water can render it difficult for utilization); and secondly, the concentration of dwellings that facilitates a high efficiency of infrastructure and services provision at both the municipal and building levels.

In addition to the potable water supply system, a sea water supply system requires a separate set of pumping, filtration, storage and distribution infrastructure at the municipal level. A dual piping system is also required to separate the distribution of potable water and salted water in multi-storey buildings. Therefore, from the viewpoint of cost efficiency in terms of both initial provision and recurring maintenance, the urban densification and high-rise built form in Hong Kong (which collectively nurture an economy of concentration "three-dimensionally") has a key role in promoting the economic viability of substituting potable water by sea water for flushing.

Since housing density is a key component influencing the urban form and its density, high residential density is a direct factor enabling the municipality to utilize an alternative water source for flushing. On the other hand, since residential density is a function of occupancy density and building density, high occupancy density and building density are considered the underlying factors contributing to the reduction of potable water use indirectly. The overall effect is significant, reducing approximately 30 percent of the domestic water consumption.

4.2.3 Irrigation Water Use

Irrigation water use varies with season, climate (and micro-environment), and extent, specifications and management of landscaping. The average irrigation water use represents approximately 3 percent (5 to 10 litres per person per day) and 30 to 50 percent (100 to 270 litres per person per day) of the domestic water consumption in the dwelling archetype in Hong Kong and North American cities respectively.
Some figures show even higher percentages of irrigation water use in the United States. According to Knopf (1991) and Moffat and Schiler (1993), the yard is responsible for 40 to 60 percent of household water consumption in most parts of the United States. Nonetheless, the large difference in the amount of irrigation water use is attributed to two main reasons:

- the large difference in the extent of open space available per occupant; and
- the difference in organization of watering system and management of landscaping area.

As a result of high building and residential densities in Hong Kong, the open space in residential estates is largely designed for shared usage, and typically in a ratio of about 1 to 2 square metre per occupant. In contrast, every single-family houses in North America has its private open space, typically in a ratio of about 100 square metre per occupant. As opposed to the communal landscaping managed by professional estate gardeners, private gardens are usually irrigated with larger quantities of water per unit area of open space. Since water supply is an inexpensive commodity in most cities, individual house owners tend to use water for irrigation inefficiently and consequently waste large volume of water. From these perspectives, higher building and residential densities are conducive to lower per capita consumption of water for domestic irrigation. The associated quantity of water savings can be significant, amounting to approximately a difference of 30 to 50 percent in the overall domestic water use. (The ultimate effects of the physical and spatial characteristics related to dwelling densification vary, though. For instance, through environmental education, government policy etc., private gardens can be provided with water-efficient landscaping [xeriscape] and more prudent water management.)

While an environmental strategy is to reduce per capita potable water use for irrigation, neighbourhood landscaping can be seen as a component of the urban ecosystem which reclaims the domestic wastewater available and closes the cycles of nutrient resource contained in the effluent. Therefore, instead of using "high-grade" potable water, a more environmentally-sensitive strategy is to irrigate residential landscaping, a "low-grade" task, with water from an alternative source such as the appropriately treated household wastewater or the rainwater harvested on-site.
4.2.4 Wastewater Reclamation

The daily quantity of wastewater discharged from household sinks, basins, baths, toilets etc. is large, amounting to approximately 200 and 250 litres per person in the typical households in Hong Kong and North American cities respectively. If the household wastewater is treated for reuse on-site, its amount will be sufficient to meet the water demand of "low-grade" domestic usage such as toilet flushing and garden irrigation. To implement the practice of cyclic water use on-site, there is little physical and spatial constraint in the case of single-family houses. As shown in Table 4.1, the amount of wastewater matches more or less the total amount of water required for flushing and irrigation, although seasonal variation may cause certain complications. Nonetheless, there are an array of examples in North America and Australia which practice the reuse of household wastewater (see Stein and Reynolds, 1992; Van der Ryn, 1978). To safeguard the healthiness of residents, irrigation with treated wastewater is usually required to be subsurface and follow other design and municipal guidelines (Athens and Ferguson, 1996). Nonetheless, the associated technologies are proven. (Although an economy of using on-site treatment and recycling is to reduce the need for public sewage connection, a barrier to the practice is regarding its high first costs to be paid by individual house owners.)

On the other hand, in Hong Kong's high-density housing estates, the environmental merit of the forth mentioned system of on-site wastewater recycling is seemingly insignificant from the viewpoint of water conservation. First, sea water is already extensively utilized for toilet flushing. Second, irrigation water use just represents a very small percentage (about 3 percent) of the domestic water consumption on average. However, if the recovery of nutrient resource is concerned, the domestic effluent from high-density housing represents a high concentration of resource which deserves attention. An advantage of implementing the recovery practice on the neighbourhood scale of individual housing estates is that it minimizes the probable complications associated with mixing domestic wastewater with the effluent from other commercial and industrial uses -- which frequently involves a complexity of chemicals and hazardous substances.
A variety of biological treatment and recycling systems have been developed for housing clusters or estates, such as "lagoon systems" and "constructed wetlands" (Athens and Ferguson, 1996; Hough, 1995; Van der Ryn, 1978). However, Hong Kong's high-density housing estates will typically face spatial constraints in accommodating those systems which operate with dependence on a high ratio of open space per resident. In addition, the close proximity between dwelling units and the "open air systems" will be unfavourable; the constrained natural ventilation would be a concern for the occupants as well as the system operation. A "closed system" with higher efficiencies in land use will be more appropriate for dense urban areas. "Solar Aquatics System" (SAS) is an example of biological wastewater treatment technology which is developed to meet these criteria.

Teal and Peterson (1993) stated, "the innovation in SAS technology involves concentrating the system, optimizing the mix of biological components, controlling the process, and treating a concentrated waste through all seasons." (p. 37). This approach to wastewater treatment is also described as "a solution which is cost effective, produces high quality effluent, is capable of dealing with strong organic waste, is self contained [in greenhouses] and therefore odour free, and visually attractive" (Nova Scotia Business Journal, 1995). The result of the SAS is a controlled ecological system of diverse biological components that speeds the removal of organic material and nutrients by bacterial degradation. In terms of the capacity of wastewater purification and nutrient reclamation, the SAS technology thus can be more efficient in its land use than the conventional wetlands system. In addition, the SAS technology can be solar-based, rather than fossil-fuel-based (Hough, 1995; Rink, 1995). The requirement of open space for installing the greenhouse system is estimated at approximately 0.8 square metre per resident for treating domestic effluent, including both blackwater and greywater (Rink, 1995; personal communication with Rink, December 1995). Despite the improved "space efficiency" of the SAS technology, its application is still marginal for most housing estates in Hong Kong where the open space ratio is typically very low (currently provided at a minimum of 1 to 2 square metres per resident for a host of communal facilities including landscaping area, playground, sports facilities, etc.).
In view of the above, on the scale of individual housing estates, Hong Kong's dwelling densification (in terms of high occupancy density, building density [in particular, low open space ratio], and residential density) impose constraints on recycling of domestic wastewater and reclamation of nutrient resource from the effluent. While technological improvements may further reduce the spatial requirements in the future, the availability of local open space per resident is evidently a constraining (or enabling) factor in the practice of on-site recycling. (Similarly, the low open space ratio also constrains the other "green" practice, such as stormwater retention.)

4.2.5 Rainwater Harvesting

In Hong Kong, as shown in Table 4.1, the probable average daily volume of rainwater collected by roof is estimated at approximately 5 to 10 litres per resident. In contrast with the corresponding figure associated with North American single-family dwelling, the per capita rainwater harvestable in Hong Kong is small -- although Hong Kong has a humid climate with annual rainfall about 2,250 mm (90 inches). An explanation is that in Hong Kong, the probable roof area of residential buildings for rainwater harvesting is small on a per capita basis. For a typical point block tower in Hong Kong, the top roof area is approximately 0.5 square metres per resident; whereas for a typical single-family dwelling in North America, the roof area is approximately 150 square metres, i.e., approximately 50 square metres per occupant given the occupancy rate of 3 persons per household. The corresponding ratio of average roof area per person is thus about 1 to 100.

According to Stein and Reynolds (1992), even at a "dry" rate of only annual 500 mm (20 inches) precipitation, a typical North American single-family house will yield about 50,000 litres per year, or on average 46 litres per person per day. However, in view of the very small roof collection area per capita (associated with densely populated high-rise building as a result of high occupancy, building, and residential densities) and the very large seasonal variation of rainfall (wet summer and dry winter), the collection and utilization of rainwater on-site is relatively ineffective in most high-density housing estates in Hong Kong.
4.3 SUMMARY

4.3.1 "Disposable" Pattern of Water Use

In most industrialized cities, the prevalent pattern of domestic water use is currently linear, single-directional, i.e., the supply of potable water is only "used" once and discharged for disposal. Potable water is perceived to be abundant in supply, although the crisis of water shortage is increasingly evident in many regions of the world (Brown et al., 1995; Girardet, 1992).

An effective strategy of water conservation in short terms is to reduce per capita consumption of potable water. The examination of Hong Kong's high-density housing shows that through the process of dwelling densification, about 30 percent of the domestic potable water use is saved. Through taking the advantage of an economy of population and building concentration, the major savings in potable water is achievable by utilizing sea water for toilet flushing. On the other hand, as a result of the emphasis on common open space use, the overall requirement for landscaping space per capita can be reduced and the demand for irrigation water is subsequently lowered. An efficiency of centralized management also further facilitates a prudent use of water for irrigation.

4.3.2 "Circular" Pattern of Water Use

In long terms, however, more prudent use of water resource and higher priorities for reclamation of nutrient resources from domestic effluent can be anticipated. On the scale of individual housing estates in Hong Kong (which can be equivalent to a town or small city in North America), an environmentally sensitive strategy is to optimize the recycling of household wastewater and reclamation of nutrient resource in the effluent on-site.

The case study of Hong Kong's high-density housing shows that the limited availability of local open space per resident potentially creates severe physical constraints to the installation of biological wastewater treatment and recycling facilities on-site. The limited availability of roof space per resident also makes the practice of rainwater harvesting relatively insignificant.
4.3.3 Conclusions

Figure 4.1 summarizes the relationships between dwelling densification and domestic water use. The "hierarchy of significance" shows the relative importance of the categories of domestic water use, and those of on-site wastewater and rainwater treatment. The criteria are made according to their potential reductions in flow quantity and/or environmental impact through the process of dwelling densification (or de-densification). Considering the issue of water conservation and nutrient reclamation, flushing water use and domestic wastewater reclamation are the priority concerns. Potable water use, a major category of water use, shows low density dependence.

The relevance to "density dependence" is addressed on the different scales of reference, i.e., in terms of occupancy density, building density (especially, open space ratio in this case), and residential density. The "+" or "-" mark represents a component of water use (or wastewater treatment) which indicates high relevance to density dependence, but the relationship can be either "positive" or "negative" in effect with respect to the concern of reducing per capita environmental impact; the "shaded" cells represents those with low density dependence. As shown in Figure 4.1, the following relationships between dwelling densification and domestic water use are identified:

• OCCUPANCY DENSITY

The implications of occupancy density on per capita water use and wastewater treatment are largely indirect, and manifested through its relationship with residential density. Through its effect on residential density which in turn fosters a centralized system using alternative water source for flushing, high occupancy density is conducive to low levels of per capita potable water consumption. Theoretically, high occupancy density facilitates the implementation of on-site recycling systems through the economies of proximity and concentration. However, an appropriate "balance" between the concentration of population and the availability of local open space for facility installation is a critical concern. When high occupancy density is in company with high building density, there can be physical/spatial constraints making the option of wastewater reclamation and reuse difficult for operation on-site.
<table>
<thead>
<tr>
<th>CATEGORY OF USAGE</th>
<th>HIERARCHY OF SIGNIFICANCE</th>
<th>Occupancy Density</th>
<th>Building Density</th>
<th>Residential Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potable Water Use</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flushing Water Use</td>
<td>1</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Irrigation Water Use</td>
<td>2</td>
<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>CONSERVATION OF POTABLE WATER</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Wastewater Reclamation</td>
<td>1</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rainwater Harvesting</td>
<td>2</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UTILIZATION OF ON-SITE &quot;WASTEWATER&quot;</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**FIGURE 4.1** MATRIX OF RELATIONSHIP BETWEEN DWELLING DENSIFICATION AND WATER USE
**BUILDING DENSITY**

Similar to occupancy density, the effect of high building density on the conservation of potable water in toilet flushing is indirectly manifested through its relationship with residential density. However, building density has direct implications on the built form and open space ratio. In Hong Kong, as a result of very high building densities, the prevalent residential buildings are high-rise. The local open space available for use is maximized through high-rise construction and communal ownership, but the ratio is still low on a per resident basis. While the resultant quantity of irrigation water use is low on a per capita basis, the high-rise built form and limited availability of open space per capita potentially impose physical/spatial constraints on the option of environmentally sensitive measures for long-term benefits, such as neighbourhood wastewater treatment and recycling system.

**RESIDENTIAL DENSITY**

As compared with other cities prevalently based on a "disposable" pattern of water use, high residential densities in Hong Kong are conducive to low per capita consumption of potable water. Through the practice of sea water flushing, the conservation of potable water is significant.

However, if a cyclic pattern of water use that emphasizes decentralized systems of on-site wastewater recycling and nutrient reclamation becomes an increasingly significant strategy in cities, a better "balance" should be provided between residential density and local open space ratio. In particular, an improvement in the open space available per resident will provide useful opportunities for long-term environmental benefit, locally and globally, i.e., to balance compactness with greenery, as advocated by Breheny et al. (1993).
5.1 OVERVIEW

5.1.1 Categorization

A fundamental premise on which this study is based is that dwelling densification has significant influence on the form of built environment, which in turn incurs significant effects on: (1) the pattern of materials use in building construction, and (2) the degrees of recyclable/compostable household solid waste to be recovered. Housing provision, which involves the initial construction, recurring maintenance and ultimate demolition of buildings, is associated with enormous amounts of material consumption. The building activities are also commonly a dominant source of solid waste in cities. On the other hand, household solid waste represents another major waste stream. This chapter thus addresses the patterns of material use related to the following two aspects.

- BUILDING MATERIAL USE
  Including material use and on-site waste generation in the processes of building construction.

- HOUSEHOLD SOLID WASTE RECOVERY
  Referring to the recovery of both household inorganic and organic solid waste.

5.1.2 Quantification

For the assessment of material input and waste output, the primary unit of measurement is "material mass/person/time". "Kg per person per year" is used throughout this chapter. ("Kg per person per day" is also included as a supplementary unit of measurement in the discussion of household solid waste, which is generated on a daily basis). Consistent with the assessment of energy use, the lifetime of a building is assumed at 50 years. The patterns of material use related to the initial and recurring building construction and final demolition are presented as average annual values over the effective life-span of a building.
5.2 BUILDING MATERIAL USE & WASTE GENERATION

5.2.1 Introduction

From a life-cycle perspective, it is useful to analyze the pattern of material use and solid waste generation associated with building construction activities according to the three distinguished stages of a building:

- Initial building construction;
- Recurring building maintenance and refurbishment over the effective life-span of the building;
- Final building demolition at the end of the effective life of a building.

Both material input and on-site solid waste output are involved in the initial and recurring building construction processes. For the demolition of buildings, only waste output is to be considered in this evaluation.

From a global perspective, housing construction consumes large quantities of material resource and has profound environmental impacts, including resource depletion (of both the renewable and non-renewable sources), global warming, loss of biodiversity, and deforestation. Locally, the construction entails heavy burdens on the capacity of landfill sites. In Hong Kong and Vancouver, for instance, the overall construction refuse is currently responsible for about 60 percent and 40 percent respectively of the total waste disposed of at landfills, representing the largest waste stream in cities (Elsie/GVRD, 1996; GVRD, 1995; HK-EPD, 1993b).

The published detail of construction and demolition waste associated with various building types is limited. Nonetheless, the construction, maintenance and demolition of housing is evidently a major source of the construction refuse in cities. For the analysis of Hong Kong's housing and North American single-family dwelling, the quantities and percentages of material use and waste output associated with the various construction stages are primarily collected from the following sources:
• Material quantities of Hong Kong's typical (35-storey) point-block residential buildings (without inclusion of car parking and podium structures) provided by Levett & Bailey Chartered Quantity Surveyors, Hong Kong (personal communication with Y. L. Si, February 1996);

• Material audit used in the background research for "Minimizing Environmental Impact of High-Rise Residential Building" (Cole and Wong, 1996);

• Composition and percentage of solid waste generated from new building construction and renovation/demolition works in Hong Kong (HK-EPD, 1993b);

• Material quantities of a typical Canadian single-family dwelling (in 2 storeys of floor area about 250 square metres, with a finished basement) estimated by Lafrenière (1994);

• Material and waste quantities of typical Canadian single-family dwellings (in 2 storeys of floor area over 300 square metres, with an unfinished basement and attached double garage) complied by Shawkat (1995).

The data, however, have varied degrees of accuracy and consistency, pending on refinement by research over time. There are also differences in the "boundary level", e.g., the extent of building services and household appliances included in the evaluation varies considerably with the researchers. Nevertheless, the quantities and percentages of the above data are adapted and approximated for use in this analysis. The primary purpose of this study emphasizes the relative orders of magnitude, rather than the precision of individual figures. In addition, this study focuses on the material use associated with structure, external envelope and interior finishes which together represent the most significant portion of resource consumption in a building. The relatively minor items, such as gravel and sand involved in excavation, backfilling, etc., are excluded from the evaluation.
5.2.2 Initial Building Material Use & Waste Generation

Table 5.1 shows the initial building material use and waste generation associated with the dwelling archetype in Hong Kong and North American cities. Both the material input and waste output are included in the evaluation. For the high-density housing in Hong Kong, the material input and waste output in the initial building processes are estimated at approximately 600 kg/person/year and 20 kg/person/year respectively. For the single-family dwellings in North American cities, the corresponding figures are estimated at approximately 820 to 1820 kg/person/year and 23 kg/person/year respectively.

- **MATERIAL INPUT**

For initial building construction, North American single-family dwellings require considerably higher per capita levels of material input than those in Hong Kong’s point block towers. The differences are largely attributed to the usage pattern of concrete and timber (the two major housing construction materials) which together represent about 90 percent of the total material input in both case dwellings. In Table 5.1, the major categories of material use in Hong Kong’s apartment building mostly show a lower per capita level of consumption than those in North America, but steel is notably an exceptional item which has a reversed relationship.

- **WASTE OUTPUT**

As shown in Table 5.1, both dwelling archetypes are associated with a similar per capita level of construction waste output by mass, i.e., some 20 kg/person/year. The waste proportion to the initial material input is 3 to 4 percent and 1 to 3 percent respectively. The higher proportion of on-site waste output in Hong Kong is mainly a result of its construction practice that has many components and assemblies processed on-site, rather than prefabricated in factories. Such practice is induced by the prevalently tight building sites and the non-modular building design that collectively limit the option and extent of prefabrication.
### TABLE 5.1: COMPARISON OF INITIAL BUILDING MATERIAL USE & WASTE GENERATION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th>Material Input</th>
<th>Waste Output (kg per person per year)</th>
<th>Waste Output (% of input)</th>
<th>Material Input</th>
<th>Waste Output (kg per person per year)</th>
<th>Waste Output (% of input)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HONG KONG</strong></td>
<td></td>
<td></td>
<td><strong>NORTH AMERICAN CITIES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dwelling Archetype:</td>
<td></td>
<td>Reference Model:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td></td>
<td>LOW-DENSITY SINGLE-FAMILY DETACHED HOUSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete / Mortars</td>
<td>500-600</td>
<td>90%</td>
<td>12.5 (2%)</td>
<td>500-1100</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62.5%</td>
<td></td>
<td>5 (1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td></td>
<td>20%</td>
</tr>
<tr>
<td>Steel / Ferrous Metals</td>
<td>30-40</td>
<td>6%</td>
<td>1 (2-3%)</td>
<td>10 - 15</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5%</td>
<td></td>
<td>0.1 (1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20%</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Timber Products</td>
<td>10-15</td>
<td>2%</td>
<td>6 (50%)</td>
<td>200-500</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
<td></td>
<td>10 (2-5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiles/Bricks/Gypsum etc.</td>
<td>1 - 2</td>
<td>&lt;1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1</td>
<td>&lt;1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>1</td>
<td>&lt;1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 - 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 - 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastics / Paints etc.</td>
<td>1</td>
<td>&lt;1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2-3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL:</td>
<td>544 to 660</td>
<td>20 kg/p/year (3-4% of initial material input)</td>
<td>825 to 1825</td>
<td>23 kg/p/year (1-3% of initial material input)</td>
<td></td>
</tr>
</tbody>
</table>

Source: (Adapted from Cole and Wong, 1996; ERM, 1994; HK-EPD, 1993b; Lafrenière, 1994; Shawkat, 1995)
Concrete and timber are the two major materials for housing construction in both cases, so that their wastes easily dominate the construction refuse. In Hong Kong's apartment buildings, concrete and timber accounts for about 60 percent and 30 percent respectively of the waste output, whereas in North American single-family dwellings the corresponding figures are 20 percent and 45 percent respectively. In general, the waste output is proportional to the material input, although the proportions (typically 1 to 5 percent) vary with the actual working process of individual materials. However, a particularly noteworthy point is that timber waste accounts for an exceptionally high proportion (approximately 50 percent) of the timber input in the case of Hong Kong, since a large proportion of the timber is deployed for temporary construction purpose. In the material audit, therefore, it is important to distinguish between the materials to be "contained" in a building and those only used in the construction processes.

The following discussion hence focuses on the three major constituents of material use associated with initial building construction: (1) concrete, (2) timber, and (3) steel.

- **CONCRETE**

The high-rise construction in Hong Kong typically uses a large proportion of concrete products in various forms, such as ready-mix concrete, concrete block (as opposed to gypsum wallboard used for partitioning in North America), screeding, etc. For the measurement by mass, the "heavy" concrete products thus collectively account for about 90 percent and 60 percent of the total material input and waste output respectively. Despite such an extensive use of concrete for structure, envelope and interior finishes etc. in the construction, the per capita material use is reduced by two factors: (1) the relatively high occupancy densities, and (2) the built form which involves high degrees of "attachment" between dwelling units leading to an efficiency of material use. On the other hand, the quantities of concrete use in North American single-family dwellings mainly vary with its size of basement. For those with a large basement, the per capita level of concrete use is comparatively high (almost double of that in Hong Kong’s apartments) due to their low occupancy density.
In Hong Kong's apartment buildings, timber is mainly used in two forms: (1) formwork for in-situ concreting, and (2) interior finishes such as parquet flooring, doors, cabinets etc. In company with the fact that the occupancy density is relatively high, the per capita consumption of timber product is hence relatively modest, representing merely about 2 percent of the total material input (or approximately 10 to 15 kg/person/year). However, in spite of the efficiency of resource use associated with apartment building construction and high occupancy densities, the per capita generation of timber waste is substantial, accounting for approximately 30 percent of the total waste output as shown in Table 5.1 (or approximately 6 kg/person/year, which is equivalent to about 50 percent of the input). Such a high proportion of timber waste generation is mainly attributed to the use of timber formwork, falsework, proppings, etc. for in-situ concreting activity. More importantly, most of the timber used and disposed of are hardwoods from tropical rainforests.

As one of the world's top ten importers of tropical timber and accounting for some 15 to 20 percent of the Region's total import of tropical hardwoods, Hong Kong has a key role in the global/regional trade of tropical hardwood timber almost out of all proportion to its geographical size. Each year, Hong Kong imports an average of almost 1.5 million cubic metres (with only about 30 percent re-exported) of logs and sawn wood, most of which is hardwood (e.g., over 96 percent by value in 1992). This is more than the United Kingdoms (1.38 million cubic metres), the Netherlands or the United States (both 0.99 million cubic metres). In Hong Kong, the principal user of tropical hardwood timber is the construction industry, which accounts for 80 to 85 percent of plywood and sawnwood retained locally, and the building construction (mainly for residential and commercial development) is the main sector of user (accounting for about 45 percent of the market by value). Particularly, for new building construction in Hong Kong, the extensive use of tropical hardwood for in-situ concreting and temporary works is a major global environmental concern (ERM, 1994).
The large amount of wood waste (as much as 90 percent of hardwood origin) is a result of the current way of design and construction which involves "non-modular" design and on-site concrete casting (as opposed to prefabricated modular system). It is often asserted that much of the timber is consumed for one-off uses in the construction, particularly in case of non-standard design. The figure reflects that the current hardwood use is in a wasteful manner, and over two-thirds of the timber waste in new building sites is from formwork-related activity. The timber waste is primarily disposed of at landfills. The heavy demand of Hong Kong's construction industry for tropical hardwood as the prime material for concrete formwork and other temporary works accelerates the already fast depleting tropical rainforests in Asia. The tropical hardwood forests (or tropical rainforests) are finite resources, and will be rapidly eradicated if the logging continues to be mismanaged or over-cut under the current economic pressures. From an environmental perspective, the sustainability of tropical rainforests is not only a local/regional issue but also a global concern. The key environmental concerns include the effects of logging on watersheds, maintenance of biological diversity (or often termed biodiversity), and balance of atmospheric carbon contents (ERM, 1994; HK-EPD, 1993b).

In contrast, timber products in form of lumber, plywood etc. are used extensively for the structure, building envelope and interior finishes of the single-family dwellings in North America, representing about 25 percent (approximately 200 to 500 kg/person/year) and 45 percent (approximately 10 kg/person/year) of the total material input and waste output respectively. In term of material mass, the comparatively high levels of timber resource input and waste output are mainly attributed to two factors: firstly, the extensive use of wood for housing construction (including the building envelope, structure, and interior finishes etc.), and secondly, the relatively low occupancy densities.
Steel is another major material used in building construction. It is commonly utilized as a structural component and for the manufacture of building services and household appliances. In Table 5.1, all the major items of material use in Hong Kong’s apartment building show a lower per capita level of consumption than those in North America, but steel is an exceptional item which expresses a reversed relationship. Steel products account for approximately 6 and 1 percent of material input in the dwelling archetype in Hong Kong and North American cities respectively. An explanation is that the use of steel as reinforcement bars is very intensive in tall concrete buildings. Therefore, despite the relatively high occupancy densities, Hong Kong’s high-rise housing involves a comparatively high per capita consumption of steel.

Although steel is a non-renewable resource, it is a recyclable material. The recovery of steel from the construction waste stream is currently a common practice in many cities. In Hong Kong, for instance, steel used as reinforcement bars, window frames, pipes and ducts, etc. is usually reclaimed during the demolition process of buildings. A portion of the recovered steel materials is recycled locally for the manufacture of steel reinforcement bars for construction use again. Another portion of them is exported for recycling elsewhere.

Despite its recyclability, the use of steel still entails significant environmental impacts associated with its extraction and production processes, such as the generation of toxic waste from coking process, wide range of stack emissions from furnace, and water contaminants from mill (Cole and Rousseau, 1991). On the other hand, steel products have relatively high energy intensities (see Section 3.1). The construction using steel products with recycled contents can have lower embodied energy, and reduce other environmental damages. From an environmental perspective, the reclamation of steel components for reuse and recycling is particularly important in the high-rise context of Hong Kong.
To summarize, in term of material use measured by mass, North American single-family dwellings are associated with higher levels of material use on a per person-year basis than Hong Kong's apartment buildings. This is largely as a result of the significant difference in occupancy density which even offsets the "negative" implications of high-rise construction. The difference in the quantities of initial construction waste output appears insignificant. However, different types of environmental implications are associated with the use of different materials. There are two noteworthy points regarding the material use for high-density housing construction in Hong Kong:

- The negative environmental implications due to an extensive use of tropical hardwood for concreting formwork (which is closely associated with the design and construction of high-rise concrete apartment buildings);
- The importance of recovering steel materials from the demolition of high-rise buildings.

5.2.3 Recurring Building Material Use & Waste Generation

Table 5.2 shows the recurring building material use (and waste generation) associated with the dwelling archetype in Hong Kong and North American cities. In this section, the material input is assumed to be equivalent to the waste output. For the high-density housing in Hong Kong, the recurring material usage in the building maintenance and refurbishment processes is estimated at approximately 60 to 80 kg/person/year. For the single-family dwellings in North American cities, the corresponding figure is estimated at approximately 100 to 150 kg/person/year. The former is hence equal to about 50 to 60 percent of the latter.

In the case of Hong Kong, the major constituents of recurring building material use are:

- concrete/mortar (about 80 percent);
- timber products (about 8 percent);
- steel/ferrous metals (about 5 percent);
- ceramic tiles/bricks, etc. (about 4 percent); and
- plastics/paints, etc. (about 3 percent).
TABLE 5.2 COMPARISON OF RECURRING BUILDING MATERIAL USE & WASTE GENERATION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th>Approximate Recurring Building Material Use</th>
<th>kg per person per year over a building life-span of 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HONG KONG</strong></td>
<td></td>
</tr>
<tr>
<td>Dwelling Archetype:</td>
<td></td>
</tr>
<tr>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td></td>
</tr>
<tr>
<td>Material Input / Output</td>
<td>Material Input / Output</td>
</tr>
<tr>
<td>(%) of initial input</td>
<td>(%) of initial input</td>
</tr>
<tr>
<td>Concrete / Mortar</td>
<td>50 - 60 (10%)</td>
</tr>
<tr>
<td></td>
<td>77 - 83 %</td>
</tr>
<tr>
<td>Steel / Ferrous Metals</td>
<td>3 - 4 (10%)</td>
</tr>
<tr>
<td></td>
<td>4 - 5 %</td>
</tr>
<tr>
<td>Timber Products</td>
<td>4 - 6 (40%)</td>
</tr>
<tr>
<td></td>
<td>7 - 8 %</td>
</tr>
<tr>
<td>Tiles/Bricks/Gypsum etc.</td>
<td>1.5 - 5 (150-250%)</td>
</tr>
<tr>
<td></td>
<td>2 - 6 %</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.2 (20%)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Glass</td>
<td>0.2 (20%)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Plastics / Paints etc.</td>
<td>1.5 - 2.5 (150-250%)</td>
</tr>
<tr>
<td></td>
<td>2 - 3 %</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>60.4 to 77.9 (say, 60-80 kg/person/year)</td>
</tr>
<tr>
<td></td>
<td>99.6 to 146.2 (say, 100-150 kg/person/year)</td>
</tr>
</tbody>
</table>

Source: (Adapted from Cole and Wong, 1996; Shawkat, 1995)
As discussed in Section 3.2.2, a very high proportion of the recurring resource use is attributed to the maintenance and replacement of interior finishes and building services in the case of Hong Kong's housing. Along with this perspective, the recurring use of concrete and mortars is largely related to the interior components such as floor screeding and wall/ceiling plastering, concrete block walls (as interior partitions), etc.; the use of timber is for flooring parquet, doors, kitchen cabinets etc.; the use of steel is for building services and appliances, etc.; the use of tiles and bricks is for interior floor and wall finishes, etc.; the use of plastics and paints is for interior decorations and finishes, etc.

On the other hand, the major constituents of building material use for recurring maintenance and refurbishment in North American single-family dwellings are:

- plastics/paints, etc. (about 50 percent);
- gypsum/tiles/bricks, etc. (about 14 percent);
- concrete/mortar (about 14 percent);
- timber products (about 13 percent); and
- steel/ferrous metals (about 6 percent).

For North American single-family dwellings, the maintenance and replacement of roofing (e.g., asphalt), carpet (e.g., vinyl), painting and insulation constitute the major significant aspects of recurring material use. The recurring use of gypsum, tiles, mortar, timber, steel, etc. is also largely related to the interior finishes and building services (Shawkat, 1995).

In view of the fact that the recurring material use is mainly dependent on the interior finishes and building services, occupancy density should thus has a key role in influencing the overall scale of resource consumption. There are variations in the usage pattern of materials (e.g., concrete block versus gypsum wallboard for interior partitioning), though. The effects of building density and residential density are insignificant.
5.2.4 Building Demolition Waste

Table 5.3 shows the estimated demolition waste output associated with the dwelling archetype in Hong Kong and North American cities. For the high-density housing in Hong Kong, the average waste output is estimated at approximately 580 kg per person per year over a 50 year life-cycle of the building. For the single-family dwellings in North American cities, the corresponding figure is estimated at approximately 800 to 1800 kg per person per year, equivalent to about 1.4 to 3 times of that in Hong Kong.

From a life-cycle perspective including the waste output associated with initial and recurring building material use, the solid waste generated from building demolition represents the most significant component, accounting for about 87 to 88 percent of the total waste output in both cases. Either from a global perspective concerning resource conservation (for both the renewable and non-renewable resources) or from a local perspective concerning the scarcity of landfilling sites, the activities of reuse and recycling are considered of increasing importance. (Reuse refers to the repeated use of a product or material in the same form but not necessarily for the same purpose; recycle is applicable to those products which are no longer usable in their present form, but their material content can be used in the manufacture of new products.) In Hong Kong, for instance, concrete debris is extensively utilized for land reclamation from the sea, and scarp steel is recycled for the manufacture of steel reinforcement bars. In Canada, on the other hand, the gypsum products disposed of are currently reclaimed and recycled for the production of wallboards. The degree and efficiency of waste material recovery vary with factors like government policy, economic incentive, and industries participation. Nonetheless, reductions in the generation of waste at the outset are the primary concern to be taken in this evaluation.

The comparatively low per capita output of demolition waste associated with Hong Kong's apartment building is thus regarded to be "positive" from an environmental perspective. The relatively high occupancy density is the key underlying factor contributing to this result.
TABLE 5.3  COMPARISON OF BUILDING DEMOLITION MATERIAL WASTE GENERATION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th>Waste Output</th>
<th>Approximate Recurring Building Material Use</th>
<th>kg per person per year</th>
<th>over a building life-span of 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>HONG KONG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dwelling Archetype:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td>Approximate Recurring Building Material Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Output</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete / Mortars</td>
<td>488 - 588</td>
<td>92 - 93 %</td>
<td>495 - 1095</td>
</tr>
<tr>
<td>Steel / Ferrous Metals</td>
<td>29 - 39</td>
<td>5 - 6 %</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Timber Products</td>
<td>4 - 9</td>
<td>1 %</td>
<td>190 - 490</td>
</tr>
<tr>
<td>Others</td>
<td>4</td>
<td>&lt; 1 %</td>
<td>107 - 202</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>525 to 640</td>
<td>(say, 580 kg/person/year)</td>
<td>802 to 1802</td>
</tr>
</tbody>
</table>

Source: (Adapted from Cole and Wong, 1996; ERM, 1994; HK-EPD, 1993b; Shawkat, 1995)
5.3 HOUSEHOLD SOLID WASTE RECOVERY

5.3.1 Introduction

Household solid waste commonly represents another major category of waste stream in cities. In Hong Kong, domestic solid waste accounts for about 30 percent of the total waste for landfilling, representing the second largest waste stream (HK-EPD, 1993b). In Vancouver, B.C., for instance, the corresponding figure is about 24 percent (Elsie/GVRD, 1996).

While the issue of municipal solid waste is usually considered a local problem regarding the shortage of landfill sites and appropriation of land base, this thesis also emphasizes their relationship with resource depletion on the regional and global scale. The reclamation of recoverable materials from the waste streams is increasingly regarded as a critical measure from an environmental perspective. On the other hand, it is useful to distinguish household solid waste into two categories according to the process of recycling: (1) “inorganic” waste such as metals, plastics, glass, etc., and (2) “organic” waste from the kitchen and yard. Waste of paper product is put under the category of “inorganic” waste, since its recycling process is similar to most other inorganic waste (like metals and plastics) that are commonly returned to the industries for processing. “Organic” waste is commonly recovered by composting method in yards.

In contrast to the construction waste, there are more published and government data available regarding the quantities and composition of household solid waste (e.g., ERM, 1993; HK-EPD, 1993b). In this chapter, the North American data is mainly derived from the figures in Greater Vancouver Regional District, Canada (e.g., Elsie/GVRD, 1996; GVRD, 1995).

5.3.2 Household Inorganic & Organic Solid Waste Recovery

Table 5.4 shows the typical household solid waste generation and recovery associated with the dwelling archetype in Hong Kong and North American cities. In this section, the waste is categorized into two major aspects: (1) organic waste, and (2) inorganic waste.
For the high-density housing in Hong Kong, the household organic and inorganic waste are estimated at 90 to 130 kg/person/year and 185 to 275 kg/person/year respectively, amounting to approximately 360 kg/person/year (or 1 kg/person/day) in total. For the single-family dwellings in North American cities, the corresponding figures are estimated at 120 to 130 kg/person/year and 320 to 330 kg/person/year respectively, amounting to 450 kg/person/year (or 1.2 kg/person/day) in total. The household solid waste generation pattern is largely dependent on social and cultural factors (such as social habits and public environmental awareness) rather than the physical characteristics of dwelling (HK-EPD, 1993b; Newman and Kenworthy, 1989). As shown in Table 5.4, the per capita generation of various types of waste in Hong Kong are lower than those in North America, except that there is a particularly higher quantity (and proportion) of plastic waste in Hong Kong (due to the extensive use of plastic bags and packaging).

Nevertheless, instead of addressing the differences in per capita quantity of the organic and inorganic solid waste generation, this section focuses on the levels of recovering reusable/recyclable materials from the waste stream. As shown in Table 5.4, the current levels of household waste recovery are estimated at approximately 110 to 140 kg/person/year (or 0.3 to 0.4 kg/person/day) in Hong Kong, and 140 to 200 kg/person/year (or 0.4 to 0.5 kg/person/day) in North American cities. Their current percentage of total household solid waste recovery is similar (about 30 to 40 percent), but their pattern of recovery is different.

In Hong Kong, over 35 percent of the municipal solid waste is currently recovered for recycling locally or overseas (HK-EPD, 1995b). Municipal solid waste is defined as the aggregates of domestic/public cleansing waste, and commercial and industrial waste (HK-EPD, 1993b). Separate data for waste recovery is unavailable for the individual sectors. In view of the fact that domestic waste typically accounts for over 70 percent of the municipal solid waste by mass, it is reasonable to assume that the recovery rate of domestic waste is close to that of the total municipal solid waste, i.e., in a range between 30 and 40 percent of the total domestic solid waste generation.
**TABLE 5.4** COMPARISON OF HOUSEHOLD SOLID WASTE BETWEEN HONG KONG'S HIGH-DENSITY HOUSING & NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE QUANTITY OF HOUSEHOLD SOLID WASTE (by fresh weight)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HONG KONG Dwelling Archetype: HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td>NORTH AMERICAN CITIES Reference Model: LOW-DENSITY SINGLE-FAMILY DETACHED HOUSE</td>
<td></td>
</tr>
<tr>
<td>Putrescibles</td>
<td>kg/p/day kg/p/year</td>
<td>kg/p/day kg/p/year</td>
<td>kg/p/day kg/p/year</td>
</tr>
<tr>
<td>Putrescibles</td>
<td>0.25-0.40 90-130 25-40%</td>
<td>0.30-0.40 120-130 25-30%</td>
<td></td>
</tr>
<tr>
<td>ORGANIC WASTE :</td>
<td>0.25-0.40 90-130 25-40%</td>
<td>0.30-0.40 120-130 25-30%</td>
<td></td>
</tr>
<tr>
<td>% RECOVERY :</td>
<td>- 50-80% of organic waste (15-25%)</td>
<td>- 50-80% of organic waste (15-25%)</td>
<td></td>
</tr>
<tr>
<td>Paper</td>
<td>0.20 75 20%</td>
<td>0.40-0.50 150-170 35-40%</td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td>0.15-0.20 55-75 15-20%</td>
<td>0.08-0.10 30-40 7.9%</td>
<td></td>
</tr>
<tr>
<td>Rags, Textiles</td>
<td>0.05 20 5%</td>
<td>0.03-0.05 15-20 3.4%</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>0.02-0.03 10 2.3%</td>
<td>0.06-0.09 20-35 5.8%</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>0.02-0.03 10 2.3%</td>
<td>0.07-0.08 25-30 6.7%</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.05-0.10 20-40 5-10%</td>
<td>0.12-0.18 45-70 10-15%</td>
<td></td>
</tr>
<tr>
<td>INORGANIC WASTE :</td>
<td>0.60-0.75 185-275 60-75%</td>
<td>0.80-0.90 320-330 70-75%</td>
<td></td>
</tr>
<tr>
<td>% RECOVERY :</td>
<td>50% of inorganic waste (30-38%)</td>
<td>25% of inorganic waste (17-18%)</td>
<td></td>
</tr>
<tr>
<td>TOTAL WASTE GENERATION :</td>
<td>1 kg/p/day</td>
<td>360 kg/p/year 100%</td>
<td>1.2 kg/p/day</td>
</tr>
<tr>
<td>TOTAL WASTE RECOVERY :</td>
<td>0.3-0.4 kg/p/day</td>
<td>110-140 kg/p/year 30-38%</td>
<td>0.4-0.5 kg/p/day</td>
</tr>
</tbody>
</table>

Source: (Adapted from Elsie/GVRD, 1996; GVRD, 1995; HK-EPD, 1993b; RCBC, 1994)
In Hong Kong, household inorganic solid waste currently accounts for 60 to 75 percent of the domestic solid waste; only the inorganic waste such as paper, plastics, metals, etc., is in the list of recovery. Paper, plastics and metals together typically constitute about 60 percent of the total quantity of household inorganic waste. The equivalent recovery rate of household inorganic waste is estimated at approximately 50 percent on average. The recovery rate of individual inorganic waste varies, though. For instance, the approximate recovery rate of paper, ferrous metals, non-ferrous metals, and plastics are 60 percent, 85 percent, 80 percent, and 50 percent respectively (HK-EPD, 1995a). On the other hand, household organic waste is usually mixed together with the inorganic waste and mostly disposed of at landfills.

Contrary to the situation in Hong Kong, both household inorganic and organic solid waste are commonly recycled in North American cities. The recovery rate is estimated at approximately 25 percent and 50 to 80 percent respectively. Overall, the current average recovery rate of household inorganic waste in Hong Kong (approximately 50 percent) is higher than that in North America (approximately 25 percent). According to Waste & Water Policy Group of Environmental Protection Department, Hong Kong (HK-EPD, 1994), there are two major factors which influence the extent of municipal waste recovery and recycling activities:

- **ECONOMIC CONSTRAINTS**
  
The economic constraint mainly refers to the high land premiums and labour cost which affect the financial viability of setting up recycling facilities and the low marketability of recovered materials and recycled products.

- **SPATIAL CONSTRAINTS**
  
The spatial constraint refers to the commonly tight interior (or exterior) condition in premises which affects the viability of waste separation, sorting, or composting activities. [This constraint is particularly evident in multi-storey apartment buildings.]
The tight spatial configuration in Hong Kong's typical high-rise residential buildings offers little room for the installing facility of waste recovery at individual apartment floors. In spite of the physical constraint, the level of municipal solid waste recovery in Hong Kong is among the highest in many industrialized cities according to a current research held by Environmental Protection Department of Hong Kong (HK-EPD). As reported by HK-EPD (1994), "despite the many local constraints... the level of waste recovery in Hong Kong is among the highest in most developed countries. The recovered waste materials include mainly paper, plastics, metals and textiles." (p. 1).

In the study, the recovery rate of major recyclable wastes in Hong Kong were compared with those in other developed countries in North America, Europe, and Asia. The wastes, which include paper, non-ferrous metals, ferrous metals, and plastics, are the major recyclable. The comparative result shows that Hong Kong has remarkably higher waste recovery rates. In Hong Kong, the recovery rate of paper, non-ferrous metal, ferrous metal, and plastic waste is over 60, 80, 85, and 50 percent respectively. In the other developed countries including the United States, the United Kingdom and Japan, the corresponding recovery rate is only about 30 to 50, 35 to 55, 15 to 60, and 5 to 10 percent (HK-EPD, 1995a).

As described by HK-EPD (1995b), the local waste recovery is achieved "through an informal system building on top of the waste collection system". To fit the vertical environment (high-rise buildings) prevalent in the territory, a two-stage waste collection and disposal system which is composed by the "primary" and "secondary" collection services is adopted in general. The first stage collection service, which is usually operated by the private sector, brings waste from household units in apartment buildings to privately/publicly operated central collection points at street level. The second stage collection service for domestic waste, which is usually provided by the Government through the municipal departments, then picks up the waste and transports it away for disposal.
Through the two-stage waste collection system in Hong Kong, waste materials with economic value are recovered from the waste stream at different points along the waste collection and disposal route. Such recovery activities are mainly practiced in an "informal way", in parallel to the waste collection system. The key players are "scavengers" (including the workers of the two-stage waste collection service) who separate valuable materials from the mixed waste stream and sell the recovered materials to waste balers for further processing. The recovered waste are either recycled locally or exported for recycling in overseas countries (HK-EPD, 1995b). The transportation and exportation of waste materials, however, have environmental costs. The concentration of waste stock in the high-density, high-rise context facilitates the informal scavenging practice through economizing handling and transportation expense. The benefit of proximity maximizes the profits obtainable from the practice of waste recovery, offsets the general economic constraint that limits the viability of waste recovery, and turns the activities (particularly for recovery of those recyclables of high marketable values) to be financially favourable (Newman and Kenworthy, 1989). As driven by the economic incentive, the development of the informal, adaptable waste recovery system (which relies heavily upon scavengers' sorting out of marketable materials from the mixed waste stream by hand) compensates the spatial constraint in the context of high density and high-rise. In short, urban densification is a significant physical catalyst inducing the viability of municipal solid waste recovery, although politically and economically the local government's direct participation in the practice of waste recovery has been minimal under a laissez-faire policy (minimal government intervention on the market systems).

However, as opposed to the practice of backyard composting in North American single-family houses, the household organic waste in Hong Kong is mostly disposed of at landfills. In Hong Kong, although the organic garbage is predominately generated from kitchens rather than yards, the proportion of putrescibles is still very significant (about 25 to 40 percent by fresh weight) in the domestic waste stream. The recovery of household organic waste is increasingly considered an important challenge in Hong Kong from the following environmental viewpoints.
• LANDFILL SITE

Many of the existing landfills have approached near capacity in recent years. Though new landfill sites and some "dumping sites" (particularly for construction refuse) associated with land reclamation are both currently being planned and constructed, reducing the disposal of wastes will be necessary to extend their useful life (ERM, 1993; HK-EPD, 1993b). More importantly, the availability of "dumping sites" is declining, and the new landfill sites are getting more remote from urban areas. This trend will result in increasing transportation expenses, and in turn generate higher energy demand and more traffic pollutants.

• RESOURCES DEPLETION

Facing the escalating size of population and rising level of per capita consumption, there is a greater urgency of resources reclamation from the waste stream at both the local and regional levels. The concerned resources include not only the non-renewable materials such as metals and plastics but also the renewable materials, such as plant nutrients which are facing a rate of depletion higher than that of replenishment (Girardet, 1992).

• OTHER ISSUES

In a landfill, organic waste breaks down anaerobically, producing methane which is many times more effective as a greenhouse gas than carbon dioxide. Throwing kitchen and yard waste out with the other household garbage for landfilling contributes to the global warming (Forst, 1996; Vale, 1991). The emission of methane, a poisonous gas, also makes the reclaimed land unsuitable for habitation. (Theoretically, the generation of methane can be collected for beneficial use; however, such practice is seldom made. Methane emissions happen to drift up uselessly, adding to the greenhouse effect.)

High building density and residential density as those in Hong Kong entail significant physical constraints on the practice of recovery and composting of household organic waste by individual dwelling units. In light of the above environmental concerns, such a physical/spatial constraint on the option of household organic waste recovery deserves particular attention and more research.
5.4 SUMMARY

5.4.1 Building Material Inputs & Waste Outputs

As shown in Table 5.5, over a 50 year life-cycle of the case building types, the material use for initial building construction typically accounts for approximately 90 percent of the total building material input (measured in term of materials mass). On a per person-year basis, the total building material input/output is 660 to 680 kg/person/year and 920 to 1970 kg/person/year for the dwelling archetype in Hong Kong and North American cities respectively, i.e., in a ratio of about 1 to 3 and 2 to 3. The significant difference in building material inputs (especially for the initial building construction) and building waste output (especially for the final building demolition) are largely attributed to the difference in occupancy densities. Moreover, on the per capita-year basis, the quantity of building waste output is higher than that of household solid waste in the respective city.

However, the high building densities (and high residential densities) in Hong Kong's housing development are conducive to a wasteful use of tropical hardwoods in the process of construction -- which in turn leads to significant environmental impacts on the regional and global scales. On the other hand, the large amount of steel used as reinforcement bars for the structure of high-rise apartment buildings deserves particular attention. The recovery of scrap steel from building demolition is an important practice, in order to reduce the overall environmental impact of high-rise construction.

5.4.2 Household Solid Waste Recovery

The percentage of waste recovery is the primary concern in this section. As induced by an economy of proximity and concentration, the recovery rate of major inorganic wastes, i.e., paper, plastics, metals etc., in Hong Kong's high-density housing (approximately 50 percent) is currently higher than that in North American cities (approximately 25 percent).
TABLE 5.5  COMPARISON OF PER CAPITA MATERIAL USE & SOLID WASTE GENERATION BETWEEN HONG KONG'S HIGH-DENSITY HOUSING & NORTH AMERICAN SINGLE-FAMILY DWELLING

<table>
<thead>
<tr>
<th></th>
<th>APPROXIMATE PER CAPITA MATERIAL USAGE PATTERN</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg per person per year</td>
<td>over a building life-span of 50 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HONG KONG</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dwelling Archetype:</td>
<td>HIGH-DENSITY MULTIPLE-FAMILY APARTMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference Model:</td>
<td>LOW-DENSITY SINGLE-FAMILY DETACHED HOUSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Material Input</strong></td>
<td><strong>Waste Output</strong></td>
<td><strong>Material Input</strong></td>
<td><strong>Waste Output</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Building</td>
<td>600</td>
<td>20</td>
<td>820 - 1820</td>
<td>90%</td>
<td>20</td>
<td>2%</td>
</tr>
<tr>
<td>Material Use &amp; Waste</td>
<td>90%</td>
<td>3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recurring Building</td>
<td>60-80</td>
<td>60-80</td>
<td>100-150</td>
<td>10%</td>
<td>100-150</td>
<td>10%</td>
</tr>
<tr>
<td>Material Use &amp; Waste</td>
<td>10%</td>
<td>10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Demolition</td>
<td>-</td>
<td>580</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material Waste</td>
<td>-</td>
<td>87%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BUILDING MATERIAL USE:</strong></td>
<td>660 to 680 kg/person/year</td>
<td>920 to 1970 kg/person/year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Waste Output</strong></td>
<td><strong>Waste Recovery</strong></td>
<td><strong>Waste Output</strong></td>
<td><strong>Waste Recovery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household Solid Inorganic Waste</td>
<td>185-275</td>
<td>60-75%</td>
<td>110-140</td>
<td>50%</td>
<td>320-330</td>
<td>68-72%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household Solid Organic Waste</td>
<td>90-130</td>
<td>25-40%</td>
<td>-</td>
<td>-</td>
<td>120-130</td>
<td>28-32%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOUSEHOLD SOLID WASTE:</td>
<td>360 kg/person/year</td>
<td>110 - 140 kg/person/year (30-38% of output)</td>
<td>450 kg/person/year</td>
<td>140 - 200 kg/person/year (32-43% of output)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
However, the possibility of recovering household organic waste by individual dwellings is constrained by the high-density, high-rise form of housing in Hong Kong. By contrast, the current approximate recovery rate of household organic waste is 50 to 80 percent in North American single-family houses. Consequently, the overall recovery rate of household solid waste (including both inorganic and organic waste) is similar in both cases, amounting to approximately 30 to 40 percent.

5.4.3 Conclusions

Figure 5.1 summarizes the relationships between dwelling densification and material use in a graphic format. The "hierarchy of significance" shows the relative importance of the categories of building material use/waste generation and household solid waste recovery. Over a 50 year life-cycle of the building, initial building material use/waste generation and building demolition waste are considered the priority concerns; recurring building material use is relatively insignificant for the measurement in terms of material input and waste output by mass.

With respect to household solid waste recovery, the recovery of inorganic waste is given a higher priority in view of its larger proportion in the household waste stream. Despite the fact household organic solid waste represents a smaller share in the domestic waste stream, the recovery of organic waste should be considered as important as that of inorganic waste from an environmental perspective.

The relevance to "density dependence" is addressed on the different scales of reference. The "+" or "-" mark represents a component of material use (or waste generation and treatment) which indicates high relevance to density dependence, but the relationship can be either "positive" or "negative" in effect with respect to the concern of reducing per capita environmental impact. The "shaded" cells represents those whose density dependence is low. As indicated in Figure 5.1, the following key relationships between dwelling densification and material use are identified:
<table>
<thead>
<tr>
<th>CATEGORY OF USAGE</th>
<th>HIERARCHY OF SIGNIFICANCE</th>
<th>OCCUPANCY DENSITY</th>
<th>BUILDING DENSITY</th>
<th>RESIDENTIAL DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Building Material Use &amp; Waste Generation</td>
<td>1</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Recurring Building Material Use &amp; Waste Generation</td>
<td>3</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Building Demolition Material Waste Generation</td>
<td>2</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

**CONSERVATION OF BUILDING MATERIAL RESOURCE:**

<table>
<thead>
<tr>
<th></th>
<th>OCCUPANCY DENSITY</th>
<th>BUILDING DENSITY</th>
<th>RESIDENTIAL DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household Inorganic Solid Waste Recovery</td>
<td>1</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Household Organic Solid Waste Recovery</td>
<td>2</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

**RECOVERY OF HOUSEHOLD MATERIAL WASTE:**

<table>
<thead>
<tr>
<th></th>
<th>OCCUPANCY DENSITY</th>
<th>BUILDING DENSITY</th>
<th>RESIDENTIAL DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**FIGURE 5.1 MATRIX OF RELATIONSHIP BETWEEN DWELLING DENSIFICATION AND MATERIAL USE**
OCCUPANCY DENSITY

High occupancy density is conducive to low levels of per capita material consumption and waste generation over a 50 year life-cycle of the building, including its initial construction, recurring maintenance and refurbishment, and final demolition. A key underlying factor is: the less the per capita floor area, the less the material consumed in the construction processes and the less the waste generated during the building maintenance and demolition. As advocated by Rousseau (1996), "a fundamental strategy for resource-efficient building is to build less and use smaller quantities of materials in the construction process." (p. IV. 100).

On the other hand, high occupancy density is indirectly conducive to high recovery rates of household inorganic waste. High residential density, which is a function of high occupancy density and building density, induces the development of an efficient centralized system of household solid waste collection and sorting, including salvaging and scavenging, of recyclable materials through the economies of scale and concentration. However, occupancy density shows low relevance to the recovery of household organic waste.

BUILDING DENSITY

High building density in Hong Kong influences both building design (including material quantities and specifications) and the way of construction. First, it leads to the high-rise form of apartment buildings, mostly constructed of reinforced concrete. The associated levels of per capita consumption of concrete and steel are high. Second, another "negative" environmental impact is associated with the use of tropical hardwood as formwork for in-situ concreting process, which not only consumes large quantities of timber for temporary tasks but also generates large quantities of timber waste in the initial building construction. The major underlying factors are associated with the non-modular design of dwelling units and the scarcity of on-site open space for prefabrication works, which are attributed to the physical and design constraints imposed by high building densities.
Similar to occupancy density, high building density is indirectly conducive to the recovery of household inorganic waste. High residential density, a function of high occupancy density and building density, induces the development of an efficient centralized system of waste collection, sorting, and ultimate recovery of recyclables. In the high-rise apartment buildings, for instance, refuse chute is commonly utilized as the means to deliver household waste from any floors to a collection point at a lower level. However, as opposed to the availability of a backyard for composting of household organic waste in North American single-family houses, the typical housing estate with high building densities in Hong Kong is commonly in short of appropriate space for the practice of composting by individual dwellings.

RESIDENTIAL DENSITY

In Hong Kong, as the effect of high occupancy densities "overrides" that of high building densities, the high residential densities are subsequently conducive to low per capita levels of construction material input and waste output. However, there are associated environmental concerns, such as the intensive use of tropical hardwood and steel. Increasing prefabrication of building components is an approach that can reduce the use of timber for temporary works; decreasing residential density (through decreasing building density) accompanied by increasing size of development site can facilitate this option. With decreasing residential density (but without changing occupancy density), the feasibility of reducing building heights can also reduce the "steel ratio" required for the structural components.

On the other hand, high residential densities correlate with high recovery rate of household inorganic waste, but entail physical constraints on the composting of organic waste by individual occupants. Based on the premise that the practice of household organic waste recovery has an increasing significance from an environmental perspective, extremely high residential density -- which physically and spatially limits the possibility of household organic waste segregation and composting -- presents a design problem that requires improvements.
An approach is the use of "in-vessel composter": a closed system for composting household organic waste. Its merits include higher efficiencies in land use and odour free [similar to the concept of Solar Aquatics System for on-site wastewater recycling, as described in Section 4.2.4]. "In-vessel composter" is designed particularly for multi-family dwellings, where individual composting space is unavailable and the extent of communal open space is limited. Some pioneer projects are being undertaken for apartment buildings in Vancouver, B.C. (personal communication, M. J. O'Donnell, UBC Waste Reduction Program, March 1996).

While the technical and operational aspects of the in-vessel composting system (or other similar technologies) are still under investigation, the principle of "source separation" of recyclable/compostable materials is considered of utmost importance. As pointed out by HK-EPD (1993b), the current practice of reclaiming recyclables from mixed wastes in Hong Kong has limited opportunities to further increase the level of recycling, since contaminants and moisture can degrade material recyclability. The recovery of organic materials from waste mixture is also evidently ineffective.

More researches now focus on source separation of recyclable waste in multi-family dwellings, and the proposals may include "chute system" or "container system" (e.g., ERM, 1993). "Chute system" uses recycling chutes to collect recyclables discarded from any floor. "Container scheme" refers to the use of bins or plastic bags in which the recyclable materials would be collected by a cleaning contractor. In practice, either of these schemes requires additional floorspace in the common areas to accommodate the facilities for waste segregation and temporary storage. However, it is difficult for many of the existing apartments to meet this "additional" requirement under the circumstance of tight internal space design as that in Hong Kong. From a long-term view, however, spatial allowance must be made during initial construction to facilitate waste segregation in new developments (Gottfried, 1996). There are implications for the dwelling densities, but the effects are potentially modest and acceptable.
CHAPTER VI
CONCLUSIONS & RECOMMENDATIONS

6.1 CONCLUSIONS

6.1.1 Per Capita Resource Use
The current rates of resource consumption and waste generation deplete nature faster than it can regenerate. The pressure on ecological integrity is mounting. To reduce per capita impact on the carrying capacity of the environment is imperative, especially in the industrialized cities. This thesis has taken Hong Kong's high-density housing as a case study to demonstrate the opportunities and constraints of dwelling densification on reducing per capita resource consumption and waste generation. Figure 6.1 compares the patterns of energy, water, and material consumption per capita associated with Hong Kong's high-density housing and North American single-family dwelling. The life-span of buildings is assumed at 50 years. In general, lower levels of per capita resource use are associated with Hong Kong's high-density housing:

- Figure 6.1a illustrates that the difference in per capita energy use is remarkable. The per capita energy consumption in Hong Kong is estimated at 15 GJ/person/year, amounting to about 15 percent of that in North America.

- Figure 6.1b presents that the per capita potable water use in Hong Kong (approximately 220 litres/person/day) is about half of that in North America. Hong Kong is also associated with lower quantities of household wastewater on a per capita basis.

- Figure 6.1c shows the per capita material consumption and waste generation associated with housing construction in Hong Kong are notably lower than those for North American single-family dwelling. The building material use is estimated at 660 to 680 and 920 to 1970 kg/person/year respectively. On the other hand, Hong Kong is associated with higher percentages of household inorganic waste recovery (60 to 75 percent by weight), but a low level of organic waste recovery.
FIGURE 6.1 COMPARATIVE PER CAPITA RESOURCE USE BETWEEN HONG KONG'S HIGH-DENSITY HOUSING AND NORTH AMERICAN SINGLE-FAMILY DWELLING
6.1.2 Dwelling Densification

This thesis has demonstrated that dwelling densification is conducive to low per capita consumption of resources and lower generation of "wastes". However, it stresses that a multitude of densities must be addressed in considering the relationships between dwelling densification and resource consumption. On the scale of residential estates, the implications of occupancy density, building density, and residential density have been explored. Each of them has its specific effects on the patterns of resource use, and their implications may reinforce or oppose one another.

OCCUPANCY DENSITY

In the case of Hong Kong, high occupancy densities (15 to 20 square metre gross floor area per person) are consistently conducive to low per capita consumption of natural resources, in particular the domestic energy and material use. The implications of high occupancy density can be interpreted in two broad ways: the "indirect" and "direct" effects. Occupancy density is defined as the ratio between the area of floorspace and occupants. If less home space is required per capita, the consumption of resources for building construction, maintenance and operations can be scaled down directly and proportionally. On the other hand, the indirect effects of occupancy density are manifested through its close relationship with residential density.

In the search for a more environmentally responsible housing design, a smaller house is considered one of the most important features (A.C.E., 1991, in Shawkat, 1995). On a per capita basis, the notion of a smaller house or dwelling unit essentially refers to a lower level of occupancy density. The underlying concept is that the floorspace available per person can be low, yet without losing any of the amenities. Appropriate compact interior layout and design (or spatial efficiency) is one of the key architectural strategies to complement this notion of a small dwelling. As contended by Van der Ryn and Calthorpe (1986), the more compact, mixed-use communities are more resource-efficient; a direction of sustainable design is that the private domain becomes more compact, but the public domain becomes more livable and diverse.
Indeed, Hong Kong's prevalent form of housing is characterized by both the compactness of private domain and the diversity of public domain. The main features of its housing design include:

- An improved efficiency of interior space use is achieved through reducing circulation space and other non-essential (or under-utilized) areas and increasing the utilization of vertical space (for storage, etc.).

- The design of space for multi-purpose contributes to the efficiency of space, while maintaining many of the desirable amenities. At home, the living space is commonly characterized by changing use at different time of a day, and the furniture is adaptable to meet the shifting patterns of internal space use (Sullivan, 1994).

- In residential estates, the communal area offers the opportunity for providing amenities that cannot be accommodated in individual small flats. A trend in Hong Kong is to increase the variety of communal facilities, such as outdoor landscape and recreational areas, indoor sports grounds, swimming pool, club house, etc. In this way, instead of having less amenities due to limited home space, there can be more overall facilities in proximity for convenient use by residents.

BUILDING DENSITY

In Hong Kong, most residential developments have high building densities. The plot ratios can be as high as 5 to 10. In company with the consideration of local open space requirement and other design issues (e.g., daylighting provision), such high levels of building density are inevitably associated with tall buildings. The current height of residential buildings is typically between 30 and 40 storeys. The vertical staggering of dwelling units is a common (but not a necessary) form of housing at high dwelling densities. Nonetheless, the widespread development of high-rise apartment buildings is a key component enabling the extremely high levels of residential density prevalent in Hong Kong, while reducing excess pressure on occupancy density and open space standards.
Again, the implications of building density on the patterns of resource use can be interpreted in terms of "indirect" and "direct" effects. As a "means" to achieving high residential densities, the extremely high building densities in Hong Kong are indirectly conducive to low overall energy consumption, low potable water use, and high recovery rate of household inorganic solid waste on a per capita basis. However, extremely high building densities potentially have direct "negative" effects on the following:

- The initial construction of high-rise housing are potentially both very energy and material intensive on a per unit floor area basis. Using initial embodied energy as an indicator, that of Hong Kong's point block tower is estimated at 5 GJ per square metre gross floor area, amounting to 1.6 times of that associated with North American single-family house.

- High-rise form of housing is often conducive to higher dependence on mechanization of household operations such as space conditioning, cloth drying, etc., while restraining the occupants from the option of harnessing ambient energy available. The increasing reliance on mechanization has significant implications on the level of fossil fuels consumption.

- In contrast to the practice of backyard composting in North American single-family dwellings, the opportunity of household organic waste segregation and recovery is also limited in the existing stock of apartment buildings in Hong Kong.

- Although the availability of local open space is often maximized by the staggering of dwelling units up to 30 to 40 storeys above ground, the open space ratio (typically about one to two square metres per resident) in Hong Kong is still relatively "low". Low open space ratios impose physical constraints to the feasibility of on-site wastewater recycling, composting, and other environmentally responsible practices that are dependent on the availability of local open space. (From an environmental perspective that increasingly emphasizes a cyclic pattern of water and resource use on-site, the search for a balance between "compactness" and open space becomes a key design challenge.)
RESIDENTIAL DENSITY

In Hong Kong, residential densities are typically in the range between 2,000 to 4,000 persons per hectare of net site area. The implications of high residential densities can be distinguished in twofold: (1) the "direct" effects on the efficiency of centralized systems, and (2) the "indirect" effects associated with high occupancy and building densities. As shown in Hong Kong, the key "direct" effects include the following:

• High residential densities are conducive to mixed landuse, pedestrianization, and an efficient use of public transportation, collectively resulting in low per capita commuting energy use. The passenger commuting energy use in Hong Kong is estimated at about 5 GJ/person/year, amounting to one-tenth of that in North America.
• The concentration of population facilitates the use of alternative water source (sea water) for toilet flushing. In this way, one-third of household potable water consumption can be saved.
• The economies of concentration and scale associated with high residential densities lead to high recovery levels of municipal solid waste, in particular the marketable recyclables such as paper, metals and plastics.

On the other hand, as a function of occupancy density and building density, the effects of residential density on the patterns of resource use can be interpreted as a combination of those associated with occupancy density and building density. However, an effect of high occupancy densities is sometimes opposite to that of high building densities. For instance, high occupancy densities correlate with low per capita level of initial embodied energy and operating energy, whereas high building densities have the opposite consequences. Overall, in the case of Hong Kong, the "positive" effects of high occupancy densities reduce or over-ride the "negative" effects of extremely high building densities, resulting in the outcomes showing that the extremely high residential densities in Hong Kong is generally conducive to low per capita resource consumption. Nonetheless, an implication is that a direction towards high occupancy density in company with moderate building density would form a greener housing alternative in long term.
6.1.3 "Green" Housing Strategy

As many other cities, Hong Kong is beginning to develop a green housing policy (e.g., see Chiu, 1996). The evaluation of dwelling densities is essentially an important component of the consideration. While the current form of dwelling densification in Hong Kong is conducive to the opportunity for low overall consumption of fossil fuels, potable water, and building materials on a per capita basis, this thesis has indicated that dwelling densification can entail an array of physical and spatial constraints on environmentally responsible practices, including:

- Maximizing ambient energy harnessing for household operations (e.g., space conditioning);
- Providing the option for on-site household wastewater treatment and reuse;
- Minimizing the use of tropical hardwood for temporary works in building construction;
- Providing the option for household organic solid waste segregation and recovery on-site.

There are potentially two broad strategies to deal with the physical constraints on resource conservation associated with high densities: (1) "innovative design", and (2) "de-densification".

There are recent housing projects that begin to explore innovative design approaches. An example is the public housing development in Area 19b of Tseung Kwan O new town (see Figure 6.2). The plot ratio of this project is about 8. The design process involves a comprehensive analysis on the local wind patterns (including the effects of surrounding high-density built environment). Wind tunnel modeling and other computational tools are used to generate building design. An aim is to achieve a similar level of spatial efficiency as the conventional point block towers, while improving the harnessing of ambient wind for most of the dwelling units. Architectural features (such as shallow, linear floor layout plan, stepping building heights, and "punching" holes through building mass at strategic locations) are designed to capture prevalent wind flows while minimizing wind blockage due to the interblock effects commonly happened in a context of high structural densities. The reduction in operating energy for space cooling is estimated at 2 to 3 GJ/person/year (ANA, 1993; ERM, 1993, Pryor and Pau, 1993b).
FIGURE 6.2  TSEUNG KWAN O AREA 19B HOUSING DEVELOPMENT: DESIGN MODEL
Another example is Tung Chung Town Centre, which is designated with a lower building density than the conventional residential estates in Hong Kong (see Figure 6.3). Tung Chung is the latest new town development in the territory of Hong Kong. The plot ratio of this project is only about 4.5 (ANA et al., 1992; Pryor and Pau, 1993b). With a lower building density, the master layout design shows that, with careful design, there can be ample opportunity for good exposure of most dwelling units to the ambient winds, and the interblock effects on wind flow can be minimized. At the same time, there can be more local open space available, over twice as that in the conventional high-density housing estates in Hong Kong. There are evidently more opportunities for on-site prefabrication of building components, wastewater recycling, composting, and other environmentally responsible practices in housing construction and domestic operations.

In the past, land resource was taken as the predominant concern in urban development. As pointed out by Trueb (1994), the scarcity of land supply in Hong Kong is largely due to political and historical reasons. Considering both the local and global environmental concerns, an alternative approach is thus to determine the housing density policy through balancing the use of key resources, including land, energy, water, and material. An appropriate level of de-densification can provide more "options" for environmentally responsive building design and domestic operations. As contended by Wackernagel (1994), the challenge of human communities is to develop a physical environment that leaves options open, rather than one which dictates resource-intensive lifestyles for the present and future generations.

Certainly, the details of "innovative design" at high dwelling densities and "de-densification" require further research. As pointed out by Owen (1991), higher density development requires more design imagination and inputs, in order to secure good daylighting and others [such as natural space cooling and more greenery]. In addition to these aspects, the following sections present some directions for further research with respect to the relationships between urban densification and resource consumption.
FIGURE 6.3 TUNG CHUNG TOWN CENTRE: MASTER LAYOUT DESIGN MODEL
DIRECTIONS FOR FURTHER RESEARCH

6.2.1 Different Densities

This thesis has illustrated that, in the discussion of the relationships between densification and resource use, the definition of density must be clear. A multitude of densities can be analyzed, according to the referred scale(s) of reference and the statistical indicator(s) used. This study has concentrated on the "micro" scales and the residential sector of the urban built environment (i.e., individual households and residential estates in the urban/suburban areas). Further research can be conducted on the other scales of reference and/or the other types of building. For instance, what is the relationship between densification and per capita resource consumption for commercial and office developments?

6.2.2 Different Cities

Comparison of resource use and built form for different cities is considered an useful approach that deepens the understanding on their interrelationships. This thesis represents a preliminary investigation comparing Hong Kong's residential estate (a very high-density model) with North American single-family dwelling (a typical low-density model). Prior to carrying out further international comparison, the acquisition of relevant local data is a necessary step. Through the process of this research, the availability of Hong Kong data was found particularly limited. Given that quantification of resource use is a useful basis for directing housing policy and design priority, the local authorities and institutes must develop a more comprehensive set of environmental data. The inclusion of other densely populated cities for international comparison can reveal more definite evidence on the relationships between dwelling densification and per capita resource consumption. As pointed out by Fouchier (1994), Hong Kong, Singapore, and Macau belong to the group of [industrialized] cities which are currently placed on top of the list of "the most densely populated territory". Each of these cities, however, has a different combination of densities and subsequently different physical and spatial configurations of dwelling.
In Singapore, for instance, the territorial density, urban density, gross and net residential densities are roughly in the order of 50, 100, 200, and 600 persons per hectare respectively; the building density, building height, and occupancy density are about 2.4 to 2.8 plot ratio, 10 to 12 storeys, and 30 square metres per person respectively (Liu, 1996; Newman and Kenworthy, 1989). (See Table 1.1 for contrast with Hong Kong.) Based on these indicators of density, Hong Kong is in general denser than Singapore, although the extent of differences varies considerably with the indicators. What are the patterns of per capita resource use in Singapore in comparison with Hong Kong? More specifically, for example, what are the environmental opportunities and constraints associated with the difference in building density (plot ratio 5 to 10 versus 2.4 to 2.8)?

As pointed out by Berkebile (1994), "it is the 'American way of life' that is one of the greatest threats to sustainability -- setting the records for consumption, waste, and pollution. Ironically, just as the flaws in these existing design is aware of, the developing world is rushing to duplicate the American way of life." (p. 5). On the other hand, Hughes (1994a) warns, "there is a danger that the architectural trappings of Hong Kong will be (and are being) adopted [by other developing Asian cities], without reference to the underlying generator."

This thesis is an attempt to make explicit some of the key environmental opportunities and constraints associated with the extremely high levels of dwelling densification in Hong Kong. In view of the profound implications of dwelling densities on the patterns of resource use in long term, an in-depth understanding of their intrinsic inter-relationships, through further international comparison and/or other methods of assessment, is considered useful in guiding "the plan for the future" -- in both the developed and developing regions. However, housing policy and design must consider a wide range of values, including economical, socio-cultural, and environmental objectives. This thesis has be centered around some of the key environmental concerns from a global perspective. The environmental issues raised are only parts of the puzzle, yet they are increasingly critical pieces that must be integrated in the sustainable design of human settlements.


HK Housing Authority (HKHA). (1994). Housing in Figures. Information Pamphlet, Hong Kong.


## APPENDIX 1: ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANA</td>
<td>Anthony Ng Architects Ltd., Hong Kong</td>
</tr>
<tr>
<td>B.C.</td>
<td>British Columbia, Canada</td>
</tr>
<tr>
<td>CMHC</td>
<td>Canada Mortgage and Housing Corporation</td>
</tr>
<tr>
<td>EPD</td>
<td>Environmental Protection Department</td>
</tr>
<tr>
<td>ERG</td>
<td>Environmental Research Group, UBC School of Architecture</td>
</tr>
<tr>
<td>FRM</td>
<td>Environmental Resources Management Ltd.</td>
</tr>
<tr>
<td>FAR</td>
<td>floor area ratio</td>
</tr>
<tr>
<td>FSR</td>
<td>floor space ratio</td>
</tr>
<tr>
<td>GFA</td>
<td>gross floor area</td>
</tr>
<tr>
<td>GJ</td>
<td>gigajoule (giga = $10^{9}$)</td>
</tr>
<tr>
<td>GVRD</td>
<td>The Greater Vancouver Regional District</td>
</tr>
<tr>
<td>ha</td>
<td>hectare (1 ha = 10,000 m$^2$)</td>
</tr>
<tr>
<td>HK</td>
<td>Hong Kong</td>
</tr>
<tr>
<td>HKHA</td>
<td>Hong Kong Housing Authority</td>
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<tr>
<td>HKIA</td>
<td>Hong Kong Institute of Architects</td>
</tr>
<tr>
<td>HVAC</td>
<td>heating, ventilating, and air-conditioning systems</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>km</td>
<td>kilometre (kilo = $10^3$)</td>
</tr>
<tr>
<td>m</td>
<td>metre</td>
</tr>
<tr>
<td>m$^2$</td>
<td>square metre</td>
</tr>
<tr>
<td>MJ</td>
<td>megajoule (mega = $10^6$)</td>
</tr>
<tr>
<td>p</td>
<td>person</td>
</tr>
<tr>
<td>PR</td>
<td>plot ratio</td>
</tr>
<tr>
<td>RCBC</td>
<td>Recycling Council of British Columbia</td>
</tr>
<tr>
<td>SAS</td>
<td>Solar Aquatics System</td>
</tr>
<tr>
<td>UBC</td>
<td>University of British Columbia</td>
</tr>
<tr>
<td>U.S.</td>
<td>the United States</td>
</tr>
<tr>
<td>WCED</td>
<td>World Commission on Environment and Development, the United Nations</td>
</tr>
<tr>
<td>WSD</td>
<td>Water Supplies Department</td>
</tr>
</tbody>
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APPENDIX 2: GLOSSARY

biodiversity  The tendency in ecosystems, when undisturbed, to have a great variety of species forming a complex web of interactions. Human population pressure and resource consumption tend to reduce biodiversity [or biological diversity] dangerously; diverse communities are less subject to catastrophic disruption (Gottfried et al., 1996).

blackwater  Wastewater generated from toilet flushing. Blackwater has a higher nitrogen and fecal coliform level than greywater. Some jurisdictions include water from kitchen sinks or laundry facilities in the definition of blackwater (Gottfried et al., 1996).

capita  one person.

composting  The process of controlled biological decomposition of organic wastes that are separated from the waste stream either at-source or in the initial stages of a recovery process. This includes backyard, neighbourhood and regional facilities (GVRD, 1995).

constructed wetland  Any of a variety of designed systems that approximate natural wetlands, use aquatic plants, and can be used to treat wastewater or runoff (Gottfried et al., 1996). As wastewater flows through the wetland, plants and naturally occurring microbes remove waste. This biological technology can be used at a variety of scales, from wastewater treatment for an individual building to treatment for entire communities (Athens and Ferguson, 1996).

construction waste  Construction waste is waste arising from any land excavation or formation, civil/building construction, roadwork, building renovation or demolition activities. It includes various types of building debris, rubble, earth, concrete, timber, mixed site clearance materials, etc. (HK-EPD, 1993b). For the purpose of this thesis, the scope is confined to the waste associated with building construction, building renovation, and demolition activities; earth and rubble (such as soil involved in excavation and bamboo used for scaffolding) are also excluded in this study.

disposable  Any product or material which is designed to be thrown away (GVRD, 1995).

domestic solid waste  According to HK-EPD (1993b), domestic/public cleansing waste covers mainly household waste and refuse collected in public cleansing activities. Household waste refers to waste generated from residential premises in the course of normal daily activities. Refuse collected in public cleansing activities is dirt and litter collected mainly from street cleansing and public litter bins.
embodied energy  The total energy that a product may be said to "contain", including all energy used in growing, extracting, and manufacturing it and the energy used to transport it to the point of use. The embodied energy of a structure or system includes the embodied energy of its components plus the energy used in construction (Gottfried et al., 1996).

greywater  Wastewater that does not contain toilet wastes and can be reused for irrigation after simple filtration. Wastewater from kitchen sinks and dishwashers may not be considered greywater in all cases (Gottfried et al., 1996). See blackwater.

gross floor area  According to Hong Kong Building (Planning) Regulations, it refers to the floor area contained by and measured from the external surface of building envelope, i.e., including all the areas occupied by structural element, and external and internal wall. Balcony, life shaft, and other common areas such as lobby and staircase are also included in the gross floor area calculation, whereas light well, refuse collection room, meter room, and some other areas specifically designated for mechanical services are commonly excluded.

municipal solid waste  Its definition varies with governments and researchers. For instance, in GVRD, municipal solid waste (MSW) generally refers to refuse which originates from residential, IC&I (industrial, commercial, and institutional), and DLC (demolition, land clearing, and construction) sources (GVRD, 1995). In Hong Kong, MSW is defined as the aggregates of domestic/public cleansing waste, and commercial waste and industrial waste; construction waste is separated as another category of waste stream (HK-EPD, 1993a, 1993b). In this thesis, the latter definition is adopted.

natural cooling  Use of environmental phenomena to cool buildings, e.g., natural ventilation, evaporative cooling, and radioactive cooling (Gottfried et al., 1996).

occupancy rate  The amount of floorspace available to each person (Hughes, 1995a).

organic solid waste  The part of the waste stream which is comprised solely of animal or vegetable matter and typically from which a compost can be produced (GVRD, 1995).

plot ratio  According to Hong Kong Building (Planning) Regulations, the plot ratio (PR) of a building development refers to the ratio between the total gross floor area and the development site area. It is equivalent to other terms such as floor space ratio (FSR) and floor area ratio (FAR).

recovery  The reclaiming of recyclable (or energy and water) from the waste stream by various methods; or the diversion of waste from disposal.
Recyclable material (or recyclable) refers to material for which appropriate processing technology has been sufficiently developed to create a product which has a beneficial end-use and a stable market (GVRD, 1995).

Recycle

The use of the material content from waste products in the manufacture of new products, including composting (GVRD, 1995). Recycled material is that would otherwise be destined for disposal but is diverted or separated from the waste stream, reintroduced as material feed-stock, and processed into marketed end-products (Gottfried et al., 1996).

Reentrant

The recessed void area which is located in-between dwelling units as commonly seen in Hong Kong's apartment buildings (see Figure 1.4). The location is commonly used as space for hanging clothes, exhausts from kitchen, bathroom and window-mount air-conditioner are also usually located in the reentrant to avoid them from direct exposure to public view.

Renewable

A renewable product can be grown or naturally replenished or cleansed at a rate that exceeds human depletion of the resource (Gottfried et al., 1996). Renewable building materials include wood, plant fibers, wool, and other resources that are potentially replaceable within a limited time period (such as a few decades or less) after harvesting (Rousseau, 1996).

Reuse

The repeated use of a product in the same form but not necessarily for the same purpose (GVRD, 1995).

Waste disposal

Waste distined to landfilling, incineration, or other disposal methods.

Waste generation

Waste disposal plus recycling (GVRD, 1995).

Waste product

A material or product which is discarded [after use] and enters the waste stream (GVRD, 1995).

Water harvesting

Collection of both runoff and rainwater for various purposes, such as irrigation or fountains (Gottfried et al., 1996).

Water reclamation

Reuse of effluent from wastewater treatment facilities through irrigation, land application, or other recycling methods (Gottfried et al., 1996). The technique of land application refers to the distribution of effluent on golf courses, farmland, or other land. This alternative to discharging treated wastewater has several benefits, including biological treatment of wastewater, recharging of groundwater, and use of the water as a resource (Athens and Ferguson, 1996).

Xeriscape

A trademarked term referring to water-efficient choices in planting and irrigation design. It refers to seven basic principles for conserving water and protecting the environment. These include: (1) planning and design; (2) use of well-adapted plants; (3) soil analysis; (4) practical turf areas; (5) use of mulches; (6) appropriate maintenance; and (7) efficient irrigation (Gottfried et al., 1996).