Investigating Low Carbon Development of High-Density Building Clusters Located around Railway Passenger Transport Hubs in China

Qunfeng Ji

Welsh School of Architecture
Cardiff University

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Abstract

China has experienced high rates of urbanisation due to the increasing housing demand in cities, resulting in high energy consumption and high carbon dioxide emissions from buildings. Moreover, transport-related carbon dioxide emissions will also show a dramatic increase because of the growing number of vehicles in the process of the rapid urbanisation. This research aims to investigate building energy consumption and transport-related carbon dioxide emissions due to mobilities of users from buildings and propose strategies to reduce their energy demand and carbon dioxide emissions in cities.

The main contributions of this research are two-fold. Firstly, in the theoretical aspect, this research fills the research gap on the combination of the carbon dioxide emissions quantification with buildings and the transport. Secondly, in the practical perspective, this research presents examples study of the carbon dioxide emissions quantification, analyses potential factors affecting energy consumption and carbon dioxide emissions, and provides strategies for low carbon city development.

This study adopts an on-site survey, questionnaires, modelling simulation, and regression analysis to explore the situations of carbon dioxide emissions in three cases, with each representing one typical location type. The study provides an understanding of the low carbon city development, investigates energy demand and carbon dioxide emissions and compares energy demand with the simulation; it examines factors including street orientation, the layout of building clusters, overshadows, and urban heat island effects with carbon dioxide emissions from building sectors. Meanwhile, this study regresses modal splits with three aspects relating to socioeconomic characteristics, travel patterns from respondents, and self-evaluation on travelling. All of these provides implications for both theoretical and practical research on low carbon city development.

List of Publications

Ji, Q., Li, C. and Jones, P. 2017. New green theories of urban development in China. *Sustainable Cities and Society* 30, pp. 248–253.

Ji, Q. and Jones, P. 2017. Operational energy/carbon dioxide emissions analysis combining building clusters and transport demand of buildings' users at the street level—a case study of Hankou railway station surroundings in China. *9th International Conference on Sustainable Development and Planning 2017.* Bristol, UK, 27-29 June, 2017. WIT Press. PP. 107-117

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Chapter 1 Introduction

1.1 Research background

1.1.1 The practical situations for low carbon development in China

Urban areas are predicted to use 71 % of the global energy-related carbon dioxide emissions, and in China, it is around 73% (Miao 2017). Moreover, China has experienced high rates of urbanisation due to increasing housing demand in cities. The floor area of buildings completed in the whole country shows a steady increase (National Bureau of Statistics of China 2017), which can be seen in Fig. 1.1. The projection of the urban energy consumption in China will increase with the continuous process of urbanisation.

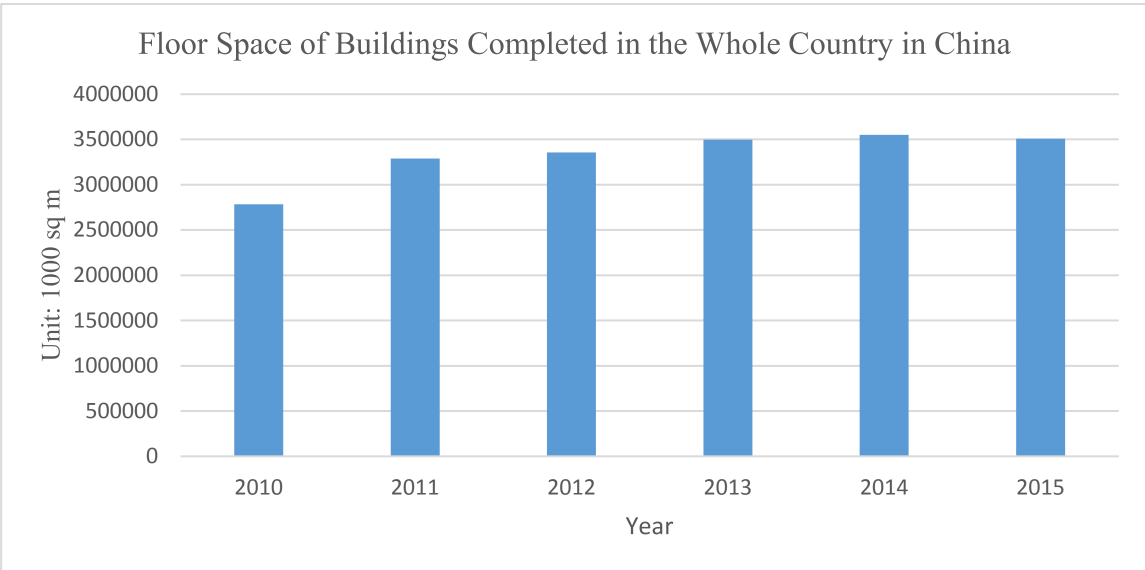


Figure 1.1 Floor space of buildings completed in China by the year 2015
Source: National Bureau of Statistics of China (2017)

The number of cities in China has increased from 193 in 1978 to 657 in 2010. By the end of the year 2017, the urbanisation rate in China was about 58.5% of the population (Fig. 1.2 shows). This rate is rapidly increasing and is expected to rise to with 75% of the population estimated by 2050 (Khanna 2014; Zhang 2015).

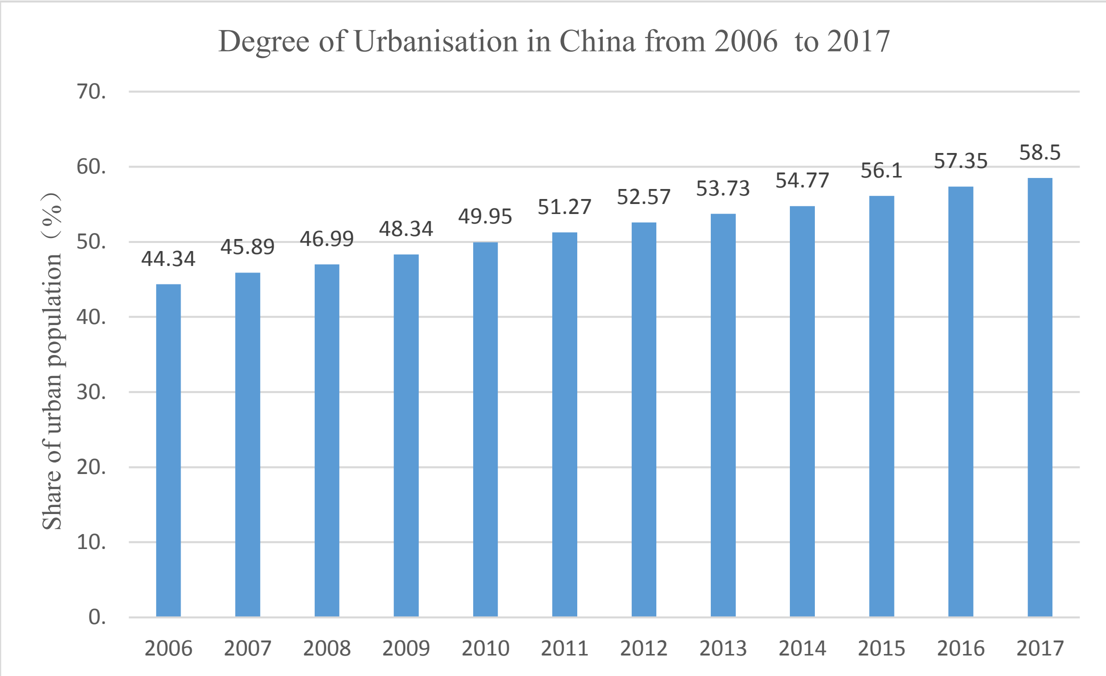


Figure 1.2 China's urbanisation rate from 2006 to 2017

Source: National Bureau of Statistics of China (2017)

More urban infrastructure and services will be needed to satisfy the demands of city residents, resulting in higher energy consumption and higher carbon dioxide emissions. Furthermore, the energy consumption in large-scale public buildings is almost ten times that of residential buildings in China (Li and Yao 2009). All these can contribute to more substantial energy demand in the process of urbanisation.

In addition, the increase in energy consumption in cities does not only result from urbanisation, but also from the development in the transport sector. Automobile emissions remain the most significant source of air pollution in cities. The pollution is the result of factors such as inappropriate urban and transport planning, inadequate public transport provision, growing vehicle numbers, and low gas emission control standards.

As stated above, there should be a new modal for urban development (i.e. the modal of green urban development in cities), and existing cities should set clear targets for carbon dioxide emissions and energy reduction (Kennedy & Sgouridis 2011). In the year 2004, the State Council approved the first Chinese Medium-and-long-term plan network, focusing on energy conservation in the transport and building sectors (Li 2006). In the following year, suggestions about prioritising the development of urban public transport systems were proposed by the Ministry of Housing and Urban-rural Development (MoHURD), and the National Development and Reform Commission (NDRC). The recent carbon dioxide emissions reduction has received unprecedented attention in the 12th Five Year Plan (2011-2015) to address climate change. During the previous 12th Five Year periods, China will comprehensively utilise various measures such as adjusting its energy structure, energy conservation, and energy efficiency, and increasing forest carbon sinks to reduce the energy consumption intensity and carbon dioxide emission intensity to a large extent. As a result, carbon dioxide emission can be controlled efficiently (Yuan and Zuo 2011).

In the worldwide context, many developed countries have taken actions and measures to achieve sustainable urban development. One of the theses actions includes promoting low carbon development in cities. These projects can be categorised into different levels, from the building level to the urban level. Regarding urban-scale projects, the Sino-Singapore Tianjin Eco-city in China and Masdar city in the United Arab Emirates have shown more comprehensive plans, including urban sustainable transport systems, renewable energy applications, innovative passive design strategies, and advanced public infrastructure systems (Premalatha et al. 2013). For the building level, there is more of a focus on low carbon building technology development and refurbishment (Gupta 2009; Anderson et al. 2015). Due to limited resources and environmental capacity at home and abroad, China is impelled to explore a path of sustainable development. Confronted with these challenges, low-carbon city development in China must become a top priority (Qiu 2009).

1.1.2 National policies to control carbon dioxide emissions

The areas around transport hubs feature more transport–related activities and different functional buildings (i.e. commercial, residential), with high density, high floor area ratio, and high urbanisation rate (Li et al. 2014). Studies show that energy demand and carbon dioxide emissions in urban areas mainly come from transport and buildings (Dai 2009; Li 2012). The problems of high-energy consumption and high carbon dioxide emissions around passenger transport hubs have become the bottleneck slowing the process of low-carbon city development. For example, a large number of automobile exhausts are polluting the ecological environment; traffic congestion has become a regular part of everyday life in hubs especially during rush hours, and therefore, the efficiency has declined sharply.

Furthermore, large areas of high-density building clusters occupy more land resources, and this can attract rural residents to flow into cities, resulting in higher energy consumption. The reason is, on the one hand, cities have been expanding their urban areas continuously, and various provinces tend to interact with each other more frequently than before; thus mobilities are constantly increasing, resulting in more transport-related energy consumption. On the other hand, the growing land development intensity has converted the simple, functional building into a more complex and multifunctional design, and this causes an increasing building energy consumption (Liang et al. 2007).

Based on the above contexts, the issues with which we are confronted are how to reduce building energy demand; how to reduce carbon dioxide emissions from the transport sector in cities, and how to guide a low carbon city development. All of these problems should be solved urgently given the backdrop of rapid urbanisation rate in China. As a result, various policies relating to low carbon development from the building sector and transport sector are proposed by the central government and carried out by the local government. For example, from the building sector, the concepts of eco-city, low carbon city, and low-carbon eco-city were initiated by the central government in 2003, 2008, and 2010 respectively. For the transport sector, the central government promotes the use of low carbon emission transport mode in cities' activities and intercity's interaction as well. NDRC promulgated the revised Mid-term and long-term railway network scheme in 2008. According to the plan, China will build more than 120,000 km of operational railway lines, including 16,000 km of passenger lines, by 2020 (NDRC 2008). Except for the existing around 10,000 km high-speed railway passenger lines that have been in operation by the end of 2013, other railway passenger railway lines are mostly designed for trains running at the speeds of 200 km/h and are due for future upgrades to reach 350 km/h. Along with the speeding up of the progress on planning and construction of passenger lines, as well as the development of building cluster towards to railways lines (i.e. TOD), China has entered a "High-speed Rail and New Urban District Times."

1.1.3 Limited research on the investigation of carbon dioxide emissions integrating buildings with transport sectors

A considerable amount of research has been carried out, at varying degrees of depth and sophistication, on how the built environments influence travel demand (Cao et al. 2009; Handy et al. 2002). The built environment is characterised by land use, densities, design features—can affect not only the number of trips generated but also modal splits and routes of travel. On the other hand, for the building sector, much of the literature on modelling building energy consumption use either the method of bottom-up or top-down at the city level or even regional level (Foliente and Seo 2012; Dall'O' et al. 2012). The problem is that both fields mentioned above researching on the energy consumption and associated carbon dioxide emissions consider the building sector and transport sector as separate aspects. The basic fact is that the high-density building clusters also always generate the amount of transport-related carbon dioxide emissions due to the mobility of users from buildings. This study combines the above two aspects, operational building energy demand and their interactions on the transport-related carbon dioxide emissions, and this can fill in the research gap which is the separate study on the energy consumption and carbon dioxide emissions from buildings and the transport.

1.2 Definitions within the Chinese contexts in this research

This sector presents clear definitions relating to the low carbon city, railway passenger transport hubs, and high-density building clusters based on the Chinese contexts.

1.2.1 Definition of low carbon city in this research

There are various concepts related to "low carbon", including low-carbon economy (DTI 2003; Xin and Zhang 2008), low-carbon society (Yang and Li 2013), low-carbon life (Goodall 2012), and low-carbon city (Qiu 2009), which reflect the issue of global climate changes caused by increasing carbon dioxide emissions from human activities. As the rapid economic growth continues and energy consumption and consequent carbon dioxide emissions increase, China is facing enormous pressure both at home and abroad to reduce its CO_2 emissions and improve its energy efficiency.

There exist different definitions of a low carbon city, but all solve the problems of increasing carbon dioxide emissions. Liu et al. (2009a) highlight that the low carbon city should integrate both elements of a low-carbon economy and a low-carbon society, provide a new model of sustainable urbanisation for China toward ecological civilisation and scientific development, and maintain safe, sustainable energy and ecological system within certain urban areas. The low carbon city is the mode of the urban construction and social development that aims to reduce carbon dioxide emission and change citizens' behaviours and ideas without compromising the quality of their life (Dai 2009). A low-carbon city in which its citizens have to promote a low-carbon economy that includes low-carbon production and low-carbon consumption in the city. Such actions help to establish an energy-saving and environment-protecting society and to build a sustainable ecological system (Yang and Li 2013). Researchers (Long et al. 2010) point out low-carbon cities must have clear, measurable evaluation indicators. The so-called "low carbon" could be an empty talk without any specific emission targets, and relevant indicators (such as per capita CO_2 emission and CO_2 emission per GDP unit) were proposed. Li et al. (2012) insist that the low carbon city is a city with clear aims and specific actions scheduled to realise both a considerable reduction of CO_2 emissions intensity in the short-term and a smooth transition to a low-carbon economy and society in the long-term.

As stated above, the definition of low-carbon city is seemly vague, but the common feature is that the low carbon city should at least have characteristics relating to sharply reduce CO_2 emissions, rely on energy efficient resources and renewable energy applications; have compact urban forms. However, what is the real low carbon city based on Chinese contexts? The low carbon city in this study includes sustainable urban forms, applications of renewable energies, low carbon transport, and energy-efficient buildings. Nevertheless, **this research focuses specifically on the reduction of carbon**

dioxide emissions as the aim for buildings and the transport sector in cities. Indicators used to measure low carbon cities are detailed in Table 1.1

Table 1.1 Key indicators for low carbon city

Source: Adapted from Baeumler et al. (2012)

Categories	Key indicators for the low-carbon city
CO_2	CO_2 emissions per capita
	CO_2 intensity
Energy	Energy consumption per capita
	Energy intensity
	The share of renewable energy
Transport	Green transport modes
Land use	Population and building density

Considering this, a conceptual low-carbon model should consist of the following primary components (also illustrated in Fig. 1.3):

- Sustainable urban forms
- Low carbon buildings
- Low carbon transport
- Applications of renewable energies

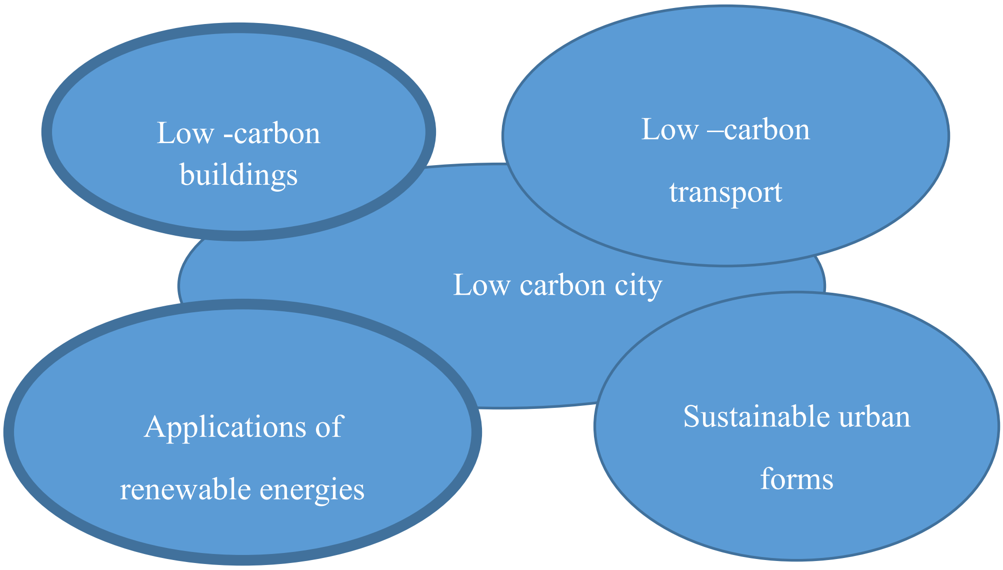


Figure 1.3 Elements for the low carbon city in this research

Source : Adapted from Baeumler et al.(2012)

1.2.2 Definition of railway passenger transport hubs

The transport hub is the functional space based on the traffic function as the primary body. Railway passenger transport hubs include the conventional railway transport hubs (Fig. 1.4, one example of the case studies) and newly built high-speed railway transport hubs (Fig. 1.5, one example of another case studies). The traditional railway transport hubs feature trains of low speed (often less than 180 km/h), small-scale, and simple function. In contrast, the high-speed railway transport hubs are the exact opposite features compared to the conventional ones. The following three aspects form the definition of a railway passenger transport hub in this study:

1) The station should be the hub of urban transport systems, covering the cities of external transport, the transfer of internal transport, and links.

2) The station should be the hub of the urban space, which leads the development and the formation of urban form and the city's most vibrant space system.

3) The station and its surrounding should be the perfect combination of mixed-land use and transport functions.

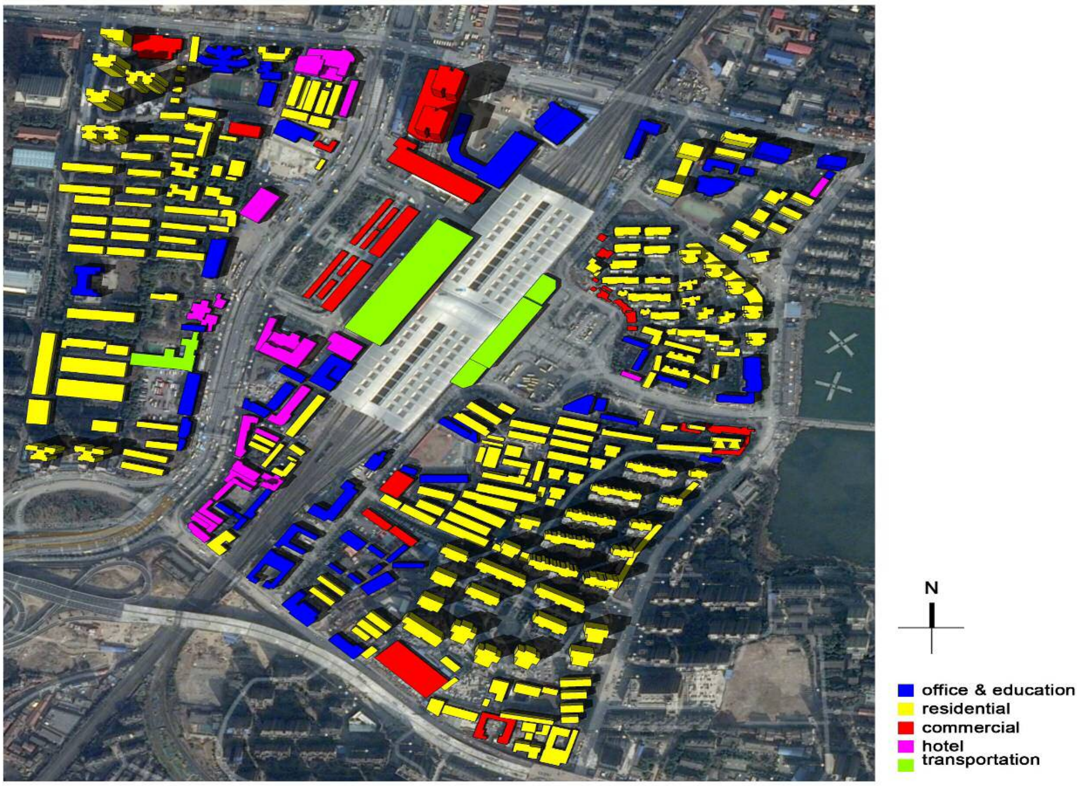


Figure 1.4 Land use around Wuchang railway station (the traditional one)

Source: Author

Figure 1.5 Land use planning around Wuhan Railway station (high-speed)

Source：Author

1.2.3 Definition of high-density building clusters around HSR stations

The high-density building cluster around HSR stations is based on the group of buildings, integrating the function of residence, commerce, office, etc. This is different from the multi-functional buildings, which is the comprehensive accumulation of the number and the categories on the synthesis. In contrast, high-density building clusters are the best combination of the various components. Moreover, high-density building clusters usually have the feature of the large spatial scales, modern urban design, and are a landmark of the local area. A typical example of high-density building clusters around HSR stations is shown in Fig. 1.6. The station seems to be a bridge that connects the two parts of the city: the existing urban centre and the HSR new urban centre.

Figure 1.6 One of the high-density building clusters around HSR stations: Tianjin West station
Source: Chen (2013)

1.3 Research aims, questions, and objectives

The aim of this research is:

- To investigate operational energy consumption and associated carbon dioxide emissions from building clusters and transport in order to reduce CO_2 emissions for low carbon city development.

The following questions are raised:

1) What should crucial factors be considered relating to energy consumption and associated carbon dioxide emissions from building clusters and from associated mobilities of users from buildings?
2) What are the appropriate methods and models that can be applied to predict operational carbon dioxide emissions from both buildings and travel activities? How do transport-related carbon dioxide emissions relate to the building sector?
3) To what extent do the selected factors (street orientation, layout, overshadowing, UHI effects, etc.) affect energy consumption and associated carbon dioxide emissions? That is, what is the relationship between energy use and selected factors?
4) What strategies can generate from this research that can be applied to control and reduce energy demand and carbon dioxide emissions from building clusters and transport in cities?

By achieving the main aims and finding answers to the research questions, this research has the following objectives:

1) To review the development of high-speed railway stations and its new urban districts in China, and to identify factors affecting energy consumption and carbon dioxide emissions largely from the field of the built environment.
2) To investigate available methods and appropriate models to predict energy consumption and associated carbon dioxide emissions from building clusters and transport due to the mobilities of users from buildings.
3) To model and simulate the energy demand and associated carbon dioxide emissions; to analyse selected variables and thus to develop a better understanding of their impacts on energy consumption and associated carbon dioxide emissions.
4) To summarise and propose strategies to reduce the energy consumption and carbon dioxide emissions from both the buildings and transport sector in cities.

1.4 Research subject and scopes

The development areas of railway passenger transport hubs can be divided into three zones, which are primary, secondary, and tertiary. These three zones are illustrated in Fig. 1.7. The primary development zones are the core area, within about 5~10 minutes walking distance from the station, and this zone plays the role of traffic services and influences the spatial layout of stations. The secondary development zones are 10~15min walking distance from the station and there are intensive and mix land uses with the function of business, office, residence, etc. The tertiary development zones form the periphery of the influencing area compared with the first two zones (Zheng and Du 2007).

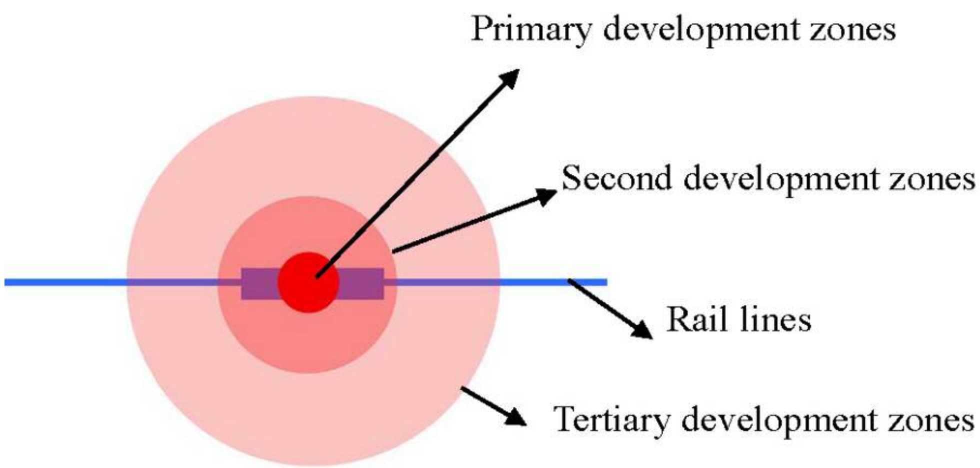


Figure 1.7 Three zones development of railway passenger transport hubs

The issues are that travel activity and building energy consumption in these zones are complex due to the various functions of buildings. The study area is in high-density building clusters located around Passenger Railway Transport Hubs (PRTHs) focusing on the second and tertiary development zones. **This is because these zones are high-density, intensive development and filled with various building functions, and have more complicated travel activities and more travel demands compared with the**

primary zone.

This research, firstly, adopts models to predict carbon dioxide emissions from building clusters and transport-related CO_2 caused by mobilities of users from buildings. The simulation and regression analysis have been conducted on the aspects of buildings and transport sectors, respectively. For the building sector, factors relating to street orientations, the layout of building clusters, overshadow, and UHI effects have been analysed. For the transport-related carbon dioxide emissions, three aspects relating to socioeconomic characteristics of the respondents, travel patterns from the interviewees, and self-evaluation of travelling are all investigated and analysed. Finally, strategies are proposed from this research to promote low carbon city development from both the building and transport sectors.

1.5 Structure of this thesis

This thesis consists of eight chapters, and it is organised as follows:

Chapter One introduces the research background. It includes the situation of high energy consumption and high carbon dioxide emissions in cities, national policies to control carbon dioxide emissions, and limited research on carbon dioxide emissions integrating buildings with transport sectors. The definitions of railway passenger transport hubs and high-density building clusters based on Chinese contexts are also clearly explained. Additionally, the research questions, aims, objectives, and contributions made by this study are also presented.

Chapter Two is the literature review and focuses on four aspects. The first aspect presents the development of high-speed railways and its stations in China as current building clusters in cities are rail-oriented development for the low-carbon purpose.

Then the theories and projects of green urban development in China have been reviewed as well as the globally typical projects. The major causative factors affecting energy consumption and carbon dioxide emissions on buildings and road transport sectors are also reviewed. Finally, approaches to modelling energy consumption and associated carbon dioxide emissions from buildings and road d transport are reviewed.

Chapter Three investigates available methods and appropriate models to understand, analyse, and predict operational energy consumption and its associated carbon dioxide emissions from buildings and transport due to mobilities of users from buildings. This study adopts methods that combine both quantitative and qualitative research. Quantitative analysis is carried out by building energy models, activities-based transport demand models, parametric analysis and multinomial logistic regression. The qualitative research includes methods of the literature analysis, on-site surveys, and questionnaires.

Chapter Four selects three high-density building clusters around three stations as case studies. Firstly, these three Cases can represent three different locations: outer city, inner city and new urban districts. Secondly, data collection relating to energy use from buildings and travel activities from the transport sector is much easier to obtain for these Cases. The purpose of this chapter is to get a better understanding of the background of three cases before modelling in the following chapter. The information relates to the geographic and climate conditions, and the general built environment development focus on buildings and the transport, all of which can help get a comprehensive understanding of these three case studies.

Chapter Five focuses on answering the question: "for the fundamental research related to the quantification of energy consumption from building clusters, what kinds of methods can be used, and how can technical tools be used to quantify carbon dioxide emissions from building clusters?" These are the questions that are answered in this chapter.

The purpose of this chapter is to apply technical tools to simulate building energy consumption, from different building categories (such as residential, office, commercial, and hotel) by integrating HTB2, VirVil Plug-in and modelling tool SketchUp. The simulation is based on building energy modelling to understand and analyse the energy performance of different building types. Additionally, the results explain differences in energy consumption of various building types.

Chapter Six focuses on answering the following question:

- What models can be applied to predict transport-related carbon dioxide emissions from travel activities due to the mobilities of users from buildings?

To answer the questions above, this research applies activities-based transport demand model to predict the transport-related carbon dioxide emissions. The results are described and analysed, and then suggestions are proposed for the reduction of transport-related carbon dioxide emissions.

Chapter Seven answers the question:

- To what extent do the selected factors affect energy consumption and associated carbon dioxide emissions.

To answer this questions, the parametric and regression analysis explore the relationship between these selected factors and their energy demand and CO_2 emissions. For building clusters, these factors focus on street orientation, the layout of building clusters, over-shadowing between buildings, and the UHI effects. For the transport sector, multinomial logistic regression analysis is applied in the option of modal splits from three aspects relating to socioeconomic characteristics of the respondents, travel patterns of the respondents, and self-evaluation on travelling.

Chapter Eight presents the conclusions of this research. Questions raised in Chapter one are answered, and the stated objectives are achieved. Implications of findings relating to strategies of low carbon city development are proposed regarding buildings and transport sectors. Finally, limitations and recommendations are discussed. Overall, this research not only presents a way to investigate the carbon dioxide emissions from an existing built environment relating to buildings and transport sectors but also gives practical suggestions for low carbon city development.

1.6 Framework of this research

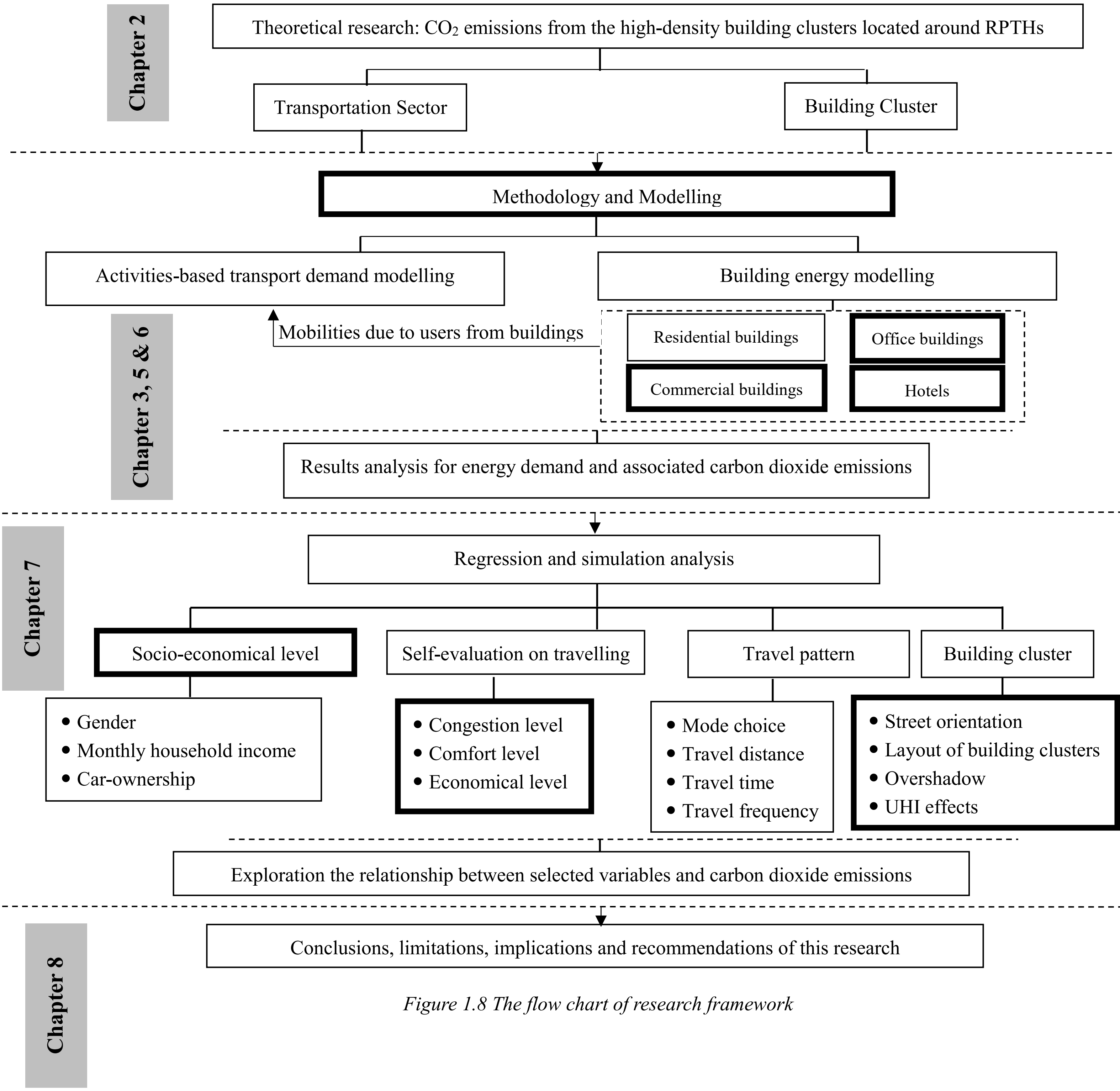


Figure 1.8 The flow chart of research framework

Figure 1.8 is the flowchart of this research framework. Firstly, literature review has been conducted relating to four aspects from building and transport sectors in Chapter 2. Then the methodology, building energy modelling, and activities-based transport demand modelling are conducted and analysed in Chapter 3, 5 and 6 respectively. Chapter 4 presents the essential background of the research object relating to three cases but is not reflected in the framework. After that, quantitative analysis from the transport sector and building sector are carried out in Chapter 7. Finally, Chapter 8 presents the conclusions, limitations, implications and recommendations of this research.

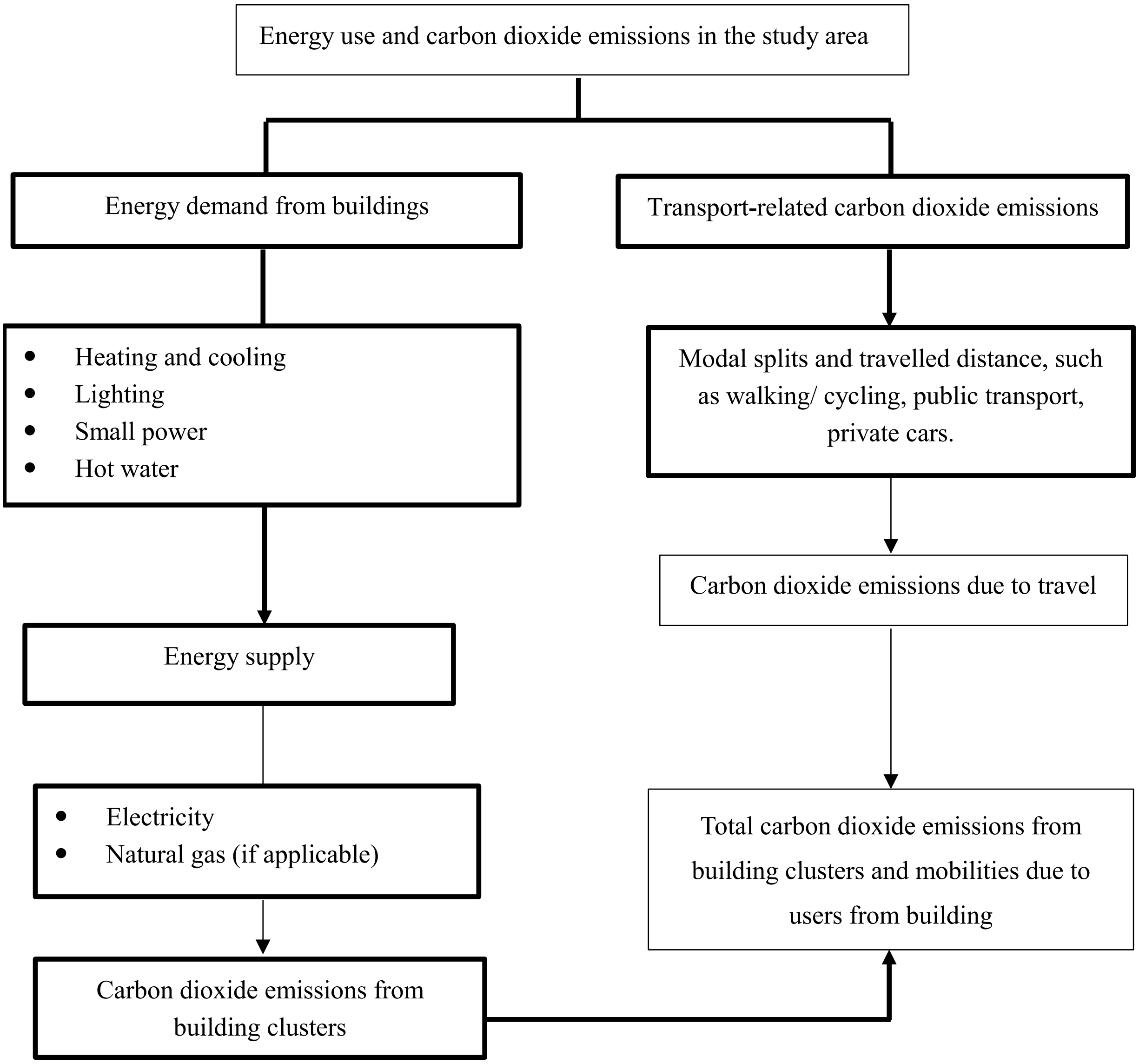


Figure 1.9 The conception model of carbon dioxide emissions from building cluster and transport due to the mobility of users from buildings

Figure 1.9 describes the process of carbon dioxide emissions from building clusters and transport sectors. For the building sector, energy supply from electricity and gas to energy demand relating to heating and cooling, lighting, small power, and hot water will generate carbon dioxide emissions. For the transport-related carbon dioxide emissions, which are caused by mobilities of users from buildings, heavily depend on the modal splits and travelled distances.

1.7 Creativity and innovation

For this research, the innovative points are presented:

(1) Most research investigates carbon dioxide emissions from buildings typically on the individual or the whole cities' scale. By contrast, this study selects three cases in a particular area, high-density building clusters around railway passenger station hubs, and each case represents one typical location relating to outer city, inner city and the new urban district. Moreover, this research explores and examines the relationship between selected factors and carbon dioxide emissions.

(2) This research is comprehensive and involves different fields, i.e. architecture, urban planning and transport planning. Moreover, past research has mainly studied the energy consumption and associated carbon dioxide emissions from buildings and the transport, separately. However, this study brings energy consumption and carbon dioxide emissions from both sectors together.

Chapter 2 Literature Review

2.1 Introduction

Chapter Two is the literature review and focuses on four aspects. The first aspect presents the development of high-speed railways and its stations in China as current building clusters in cities are rail-oriented development for the low-carbon purpose. Then the theories and projects of green urban development in China have been reviewed as well as the globally typical projects. The major causative factors affecting energy consumption and carbon dioxide emissions on buildings and road transport sectors are also reviewed, **which diretly answer the question one from theretical aspects**. Finally, approaches to modelling energy consumption and associated carbon dioxide emissions from buildings and road transport are reviewed. Fig. 2.1 presents the flowchart of Chapter 2.

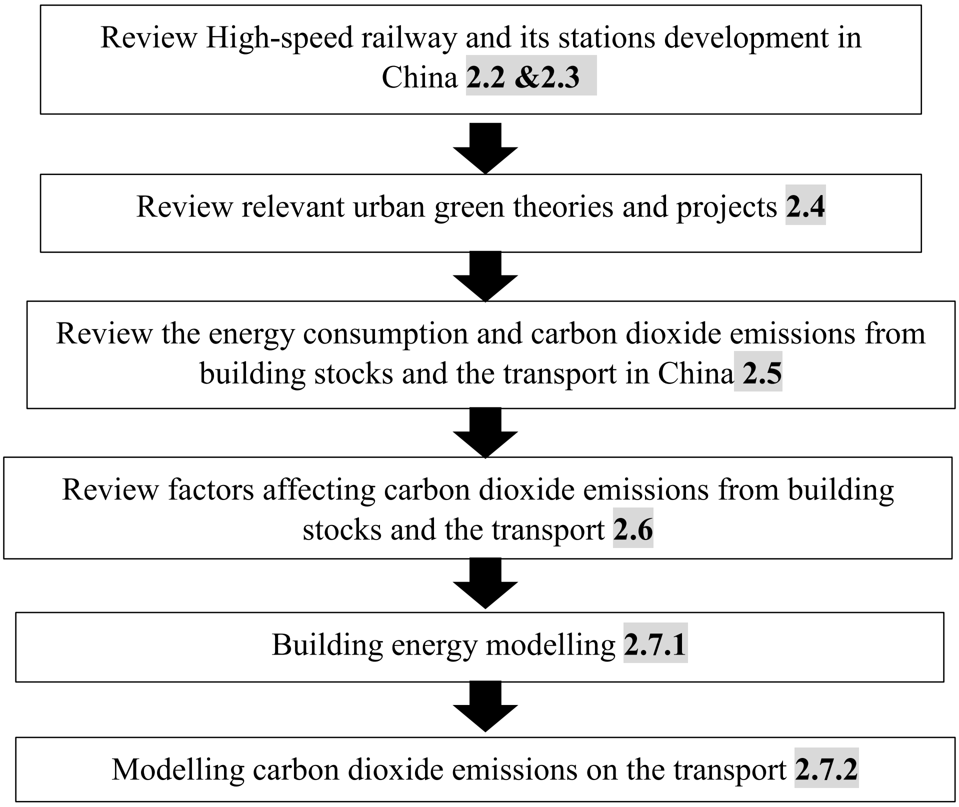


Figure 2.1 The flowchart of literature review

2.2 High-speed railway development in China

Noticeable achievements in urban transport are the rapid development of high-speed railway systems in China. The high-speed railway (HSR) systems have given priority to urban transport development. China's HSR network became one of the largest countries in the world in 2010 due to strong government support and consistent investment (Li 2009). The HSR networks consist of four primary north-south HSR lines (four vertical lines) and four east-west HSR lines (four horizontal lines) in the 2004-2008 plan (Fig. 2.2). These eight HSR trunks lines connect most of the provincial capital cities and cover most of the cities with the population of more than one million (Sun 2015).

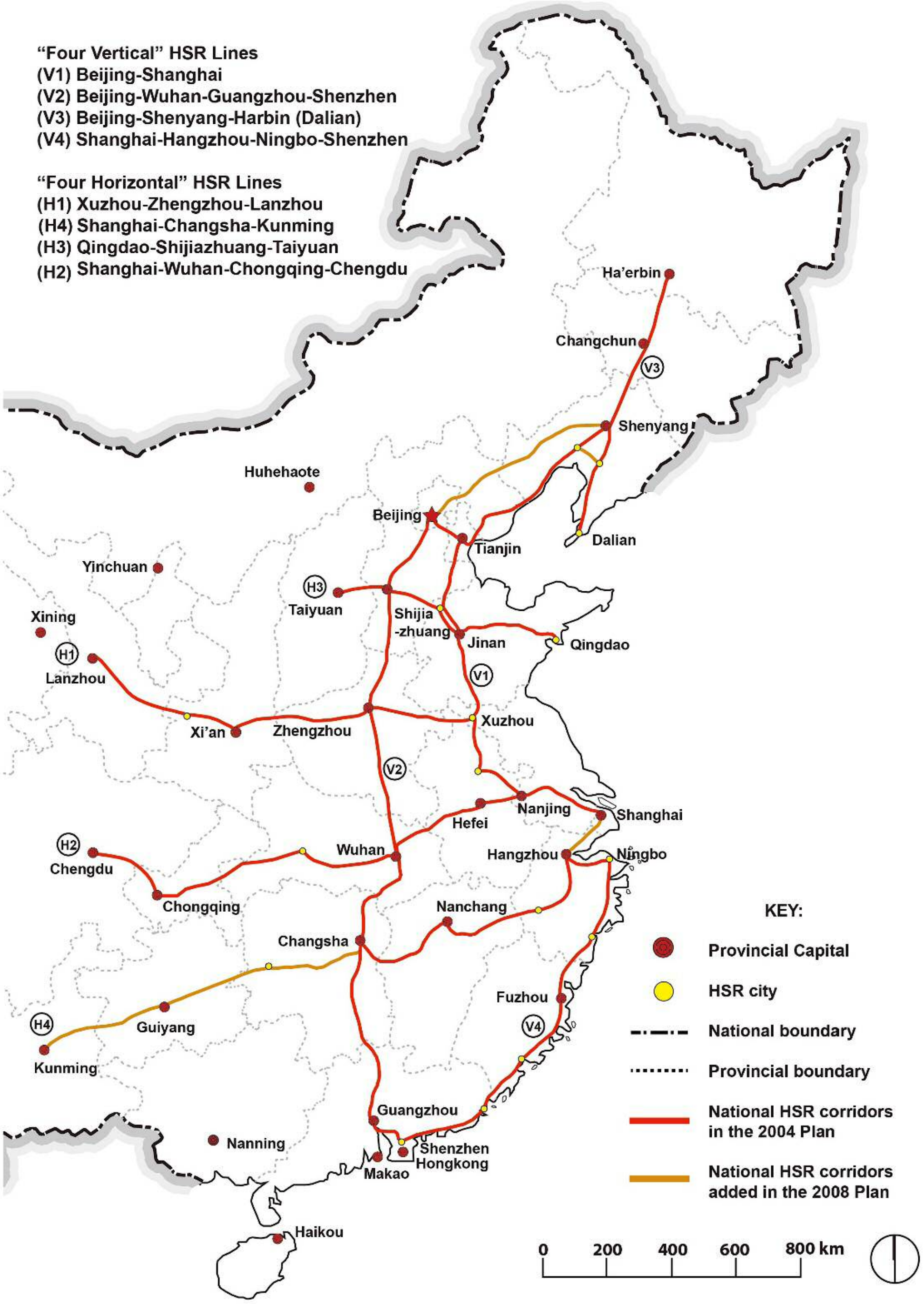


Figure 2.2 China's high-speed railway construction in the mid-to-long term plan (2008 revision)

Source: Sun (2015)

The 11th Five-year Plan (2006–2010) strengthens Beijing, Shanghai, Guangzhou, and Wuhan rail linkages, turning them into major railway transport hubs. The 12th Five-year Plan (2011–2015) extends the high-speed network to more than 11,000 km by the end of 2013 from the early around 670 km in 2008 (National Bureau of Statistics of China 2014) (Fig. 2.3).

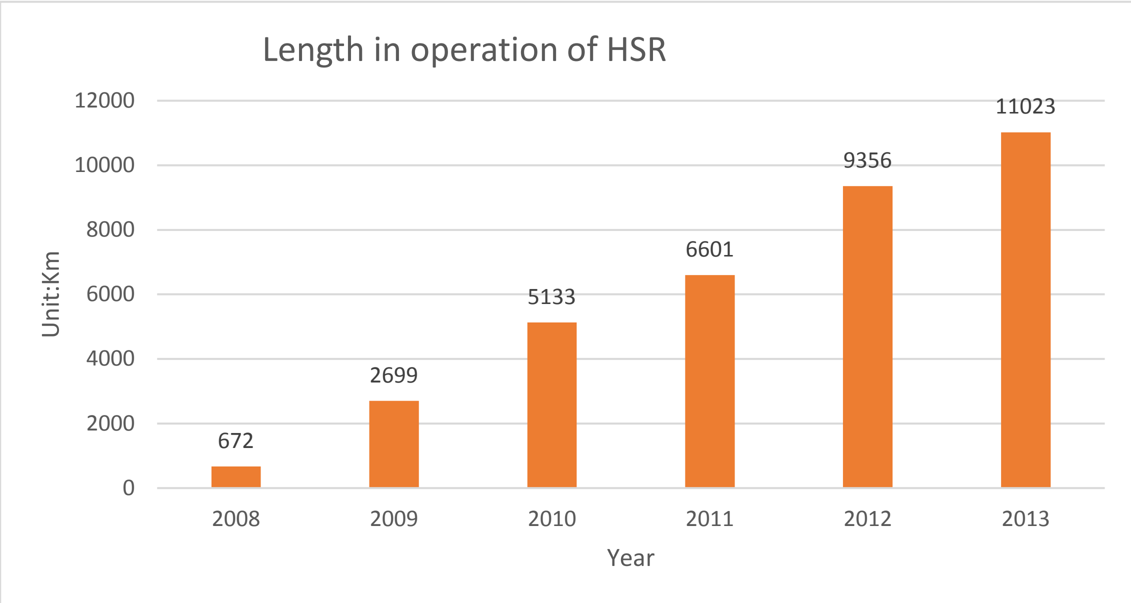


Figure 2.3 Length in the operation of HSR in China

Source: National Bureau of Statistics of China，Yearbook (2014)

The new stations are planned as a large distribution centre, and the dimension of stations are set according to the estimated number of passengers by the year 2020, making it necessary to locate in peripheral urban areas where it is relatively distant from the city centre (Li 2012). Taking Wuhan-Guangzhou line for example, it is operated in late 2009, 17 out of 18 HSR stations are newly built and are in the periphery (Takagi 2011). The first operation of the Guangzhou–Wuhan High-Speed Rail in 2009, marked a new era of China high-speed railway transport. As a result, travel time has sharply decreased from previous 12 hours to current 4 hours between Guangzhou to Wuhan. These stations usually on the edge of large cities. According to the revised medium-and long-term railway network plan of China, the total mileage of China's over-250 kilometre-per-hour railway lines (high-speed railway lines) will reach 16,000 km and will link all provincial capital cities with a population of over five million by 2020 NDRC (2008).

2.3 High-speed railway stations and new urban districts development in China

The international theoretical and practical studies suggest that the construction of high-speed rail (HSR) usually influences the development of surrounding area (Yu et al. 2012). China's HSR is promoting the construction of a series of new railway stations, which is intended to improve urban development and urban sprawl by way of rail-oriented development. Areas around the HSR station can become the new urban district, and a major node of the urban transit network (Tang et al. 2011).

In China, the large-scale construction of HSR, together with the rapid urbanisation, makes such influence more complex and profound. In the development of HSR, it works as an "amplifier". Thus it promotes suburbanisation. As for the construction of HSR stations, it can be grouped into three categories by the location to the city centre: located in the city periphery, located in the existing city centre, and located in the new districts (Sun 2015). Figure 2.4 describes the spatial distribution of HSR lines, stations, city centre, and the urban territory where the lines pass through. Stations in type 2 and 3 are all located in the urbanised areas, while station in type 1 is situated on the periphery of the city. The total difference between the station in type 2 and 3 is their development process. In other words, stations in type 3 are in the new urban district formed by the development of the stations (also called HSR new urban district), while station in type 2 is in the existing city centre of redeveopment.

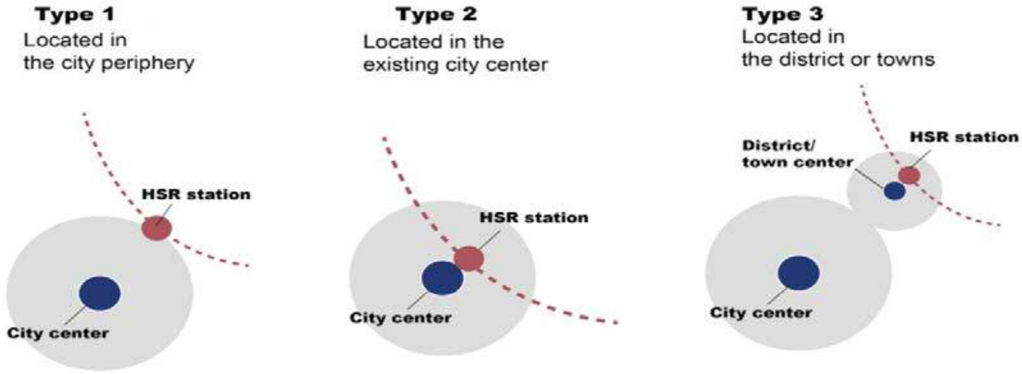


Figure 2.4 Three types of HSR stations in China
Source: Sun (2015)

Furthermore, in attempt to capitalise on the high property values caused by high-speed railway stations development, many cities have planned new urban districts next to HSR stations. Taking Beijing-Shanghai HSR lines for an example, 16 out of 24 cities have planned new urban areas around the HSR stations, as local authorities view HSR as opportunities to boost economic growth, and always take these HSR stations as seeds to develop or redevelop cities (Li 2012). The proliferation of these HSR stations will fundamentally change the existing urban structure and environments. If the HSR stations are completely newly built in the city's periphery, the HSR new urban district around HSR stations will generate (Sun 2015).

2.4 Theories and projects of green urban development in China

In modern society, the ecological theory of urban development has evolved with an increasingly better understanding of green development. The modern theory also linked with commonly used terms back in urban planning and architecture, from the beginning of the green city to low carbon eco-city.

Theories about low-carbon city development are illustrated elaborately, especially based on Chinese contexts. At the same time, good examples of the low-carbon city are presented in both China and the worldwide. The correlation and comparison of some relevant concepts, aims, and their concerns are analysed.

There are some related terms relating to low-carbon, such as low carbon life, low carbon transport, low carbon city. In 2003, the British government published "Our future energy: creating a low-carbon economy" (Department of Trade and Industry 2003), whose aims were to achieve more economical products and high-quality living standards with less energy consumption and environmental pollution and emphasises on high energy efficiency, optimised energy structure and rational use. "Low-carbon economy" came up with for the first time but did not give precise definitions.

In 2007, scholars (Skea and Nishioka 2013) proposed the concept of low carbon society, focusing on the transformation of living styles and the consumption concept. As Skea and Nishioka (2013), cited in National Institute for Environmental Studies (2006, pp. ii-iii), defines a low carbon society as follows:

- *take actions that are compatible with the principles of sustainable development, ensuring that the development needs of all groups within society are met*
- *make an equitable contribution towards the global effort to stabilise the atmospheric concentration of CO_2 and other greenhouse gases at a level that will avoid dangerous climate change, through deep cuts in global emissions*
- *demonstrate a high level of energy efficiency and use low-carbon energy sources and production technologies*
- *adopt patterns of consumption and behaviour that are consistent with low levels of greenhouse gas emissions.*

In 2009, South Korea launched low-carbon green city project (Kwang-ik 2010). The provincial government formed a Green Growth Board, and Gangneung city was selected as the low-carbon green city pilot project. It was under construction collaborated by Gangwon-do government and Ministry of Environment.

Steady economic growth and social development are accompanied by the process of rapid urbanisation since China implemented reform and open-up policy. A policy of restraining the scale of large cities and developing small cities was employed as the primary approach for achieving urbanisation at the earlier of the 1980s (Li 2011). The overall number of cities in China increased dramatically during these periods. On the contrary, existing cities were expanded through migration from the countryside in developed countries (Anderson and Ge 2005).

Recognising the limited resource and environmental challenges of its current urban development patterns, Chinese leaders have made ambitious commitments to reduce carbon dioxide emissions intensity and proposed different concepts and approaches to urban development in various periods based on Chinese contexts. Since the earlier of the 1990s, China began to explore some more sustainable ways to urban development. Central governments proposed numerous green concepts of city development and local authorities implemented these projects at different times, such as green city, national garden city, and national environmental protection model city (Peng 2010). Following entry into the 21st century, China's urban development has been under pressure to move towards a more self-sufficient, energy efficient, and environmentally-friendly model. Through central government policy guidance, local implementation, and cooperation with international partners, China has proposed more comprehensive green city concepts and the growth of city initiatives in the post-2000 era. Examples include the concept of the eco-city, low-carbon city, and low-carbon eco-city (ibid.).

2.4.1 Green city

The "Green City" was firstly seen in the exhibition "Bright City" plan in the 1930s whose ideas are to embody the city centralisation. The evolution of the green cities theory has gone through three stages, which are embryonic, formative and establishment stage (Zhao and Zhang 2013). Over the past two decades, scholars all over the world have tried to define green cities regarding development patterns, ecosystem, and city design. In China, there is no evidence showing that any official departments or organisations came up with this concept, but it has been utilised at the local level, such as governments, companies, and NGOs since the 1990s.

In the beginning, the green city concept has been explained as expanding green spaces or landscape in cities in China, but this changed later as sustainable development gradually began to come into the eye of local and central governments (Liu et al. 2014). Now it is also interpreted as environmental, economic and social aspects of development in China (ibid.). However, this concept is only used as a theory rather than in practical projects in the Chinese contexts due to its extreme ambiguity and various definitions and guidelines. China should learn from that overseas experience of urban transition, such as institutional design, cultural construction, technological innovation and urban planning, thus promoting urban transition based on national conditions.

2.4.2 National garden city

The concept of garden city was proposed back to 1898, and the goal was to combine the attractions of town life with access to nature and a healthier lifestyle (Howard 2010). In his words:

> *Its (the Garden City's) chief claim upon the attention of the public lies in the fact that it combines the important features of several schemes which have been advocated at various times, and so combines them so as to secure the best results of each, without the dangers and difficulties which sometimes, even in the minds of their authors, were clearly and distinctly seen. Shortly stated my scheme is a combination of three distinct projects which have, I think, never been united before* (Howard 1985, Chapter 10 p.83)

However, the ideology is different from the garden city and the green city. The garden city reflects the urban decentralisation. In contrast, the green city emphasises city on centralisation. Although the viewpoint of urban layout between urban decentralisation and centralisation is opposite, the fundamental starting points of two ideas are consistent. Both reflect the principles of green, maximise the urban public green spaces and increase open spaces to achieve the harmony of city and nature using the overall size reduction or density increase.

In China, one of the central governments, the Ministry of Housing and Urban-Rural Development (MoHURD) came up with a concept entitled National Garden City as early as in 1992 and by the end of 2010. In June 2004, MoHURD decided to initiate the establishment of Eco-garden City based on the program on National Garden City. MoHURD also issued a series of rules and regulations and then updated them frequently to encourage the construction, evaluation, and promotion. In these rules, the concept of National Garden City focuses heavily on landscape and green space coverage in cities, and the aims are to improve the environmental quality of urban ecology (Liu et al. 2014).

2.4.3 National environmental protection model city

The Ministry of Environmental Protection (MEP) initiated the National Environmental

Protection Model City's theory in 1997, and its concept was defined it as a city with rapid economic growth, a clean and beautiful environment, and healthy ecosystems (Liu 2014). However, the focus is not just on environmental aspects and the evaluation indicators but also on economic growth, energy efficiency, environmental protection, and construction of infrastructure (MEP 2009). By early 2012, many cities had been awarded as the National Environmental Protection Model City status, seeing Tables 2.1:

Table 2.1 National model city for environmental protection list

Source: http://english.mep.gov.cn/inventory/Model_cities/

Year	Number	Cities
2012	10	Langfang City, Zhenjiang City, Jurong City, Daqing City, Shaoxing City, Zhuji City, Weihai City, Rongcheng City, Wendeng City, Rushan City
2011	12	Yichang City, Lin'an City, Huai'an City, Foshan City, Liaocheng City, Qingpu District of Shanghai City, Linyi City, Dongguan City, Xuzhou City, Yinchuan City, Wujiang City, Zhongshan City
Former Model Cities to be Examined and Approved		
2007	4	Guangzhou City, Shouguang City, Taizhou City, Yiwu City
2006	11	Tianjin City, Ma'anshan City, Langfang City, Pudong New District of Shanghai City, Beifu District of Chongqing City, Nantong City, Huzhou City, Zhaoqing City, Quanzhou City, Yixing City, Jimo City, Pingdu City
2005	9	Chengdu City, Fuyang City, Baoji City, Guilin City, Jiaonan City, Laixi City, Rizhao City, Penglai City, Weifang City
2004	11	Mianyang City, Wuxi City, Jintan City, Liyang City, Fuzhou City, Changzhou City, Shenyang City, Karmay City, Korla City, Jiangmen City, Yubei District of Chongqing City
2003	2	Nanjing City, Dongying City
2002	6	Huizhou City, Zhaoyuan City, Haimen City, Changchun City, Yangzhou City, Jiaozhou City
2001	4	Hangzhou City, Ningbo City, Changshu City, Taicang City
2000	2	Qingdao City, Jiangyin City
1999	5	Haikou City, Shantou City, Suzhou City, Dagang District of Tianjin City, Minhang District of Shanghai City
1998	3	Kunshan City, Yantai City, Laizhou City,
1997	5	Zhangjiagang City, Shenzhen City, Dalian City, Zhuhai City, Xiamen City

These three above major green theories in China were mainly proposed between the year 1990 and 2000, but after entering the 21 centuries, the environment has continued to deteriorate. The Chinese government has taken further steps to establish a national sustainable development as the urban development strategy. Due to the different responsibilities, the Ministry of Environmental Protection (MEP), the National Development and Reform Commission (NDRC), and the Ministry of Housing and Urban-Rural Development (MoHURD), launch three programmes of eco-city, low carbon city, and low carbon eco-city, respectively.

2.4.4 Eco-city

The term “eco-city” was coined by Register in 1987, who provided inspirational guidance for making cities ecological in a visionary book entitled Eco-city Berkeley (Register 1987). However, there has not been a commonly accepted definition. Much of our understanding of the concept and the practical initiatives of eco-cities resulting from this concept has been influenced by the research of urban ecology.

In China, applying ecological principles to urban planning started in the late 1980s at the local level and later to the national level. “Guidelines for Building National Eco-Demonstration Communities (1996-2050)” was issued in 1995 by the MEP, where the concept of “Eco-community” was first proposed officially (Liu et al. 2014). The target of building eco-demonstration communities is to protect and rebuild the eco-environment, improve the traditional resource-dependent development model, achieve higher economic development at a lower resource and environment cost. Also, the aim is to make socially, economically and environmentally sustainable development.

The concept of some much larger initiatives such as Eco-counties, Eco-cities and Eco-regions were proposed by the MEP in 2003 under its “Development of indicators for the national ecological county, municipality and province (trial)" and a revised version of the standards in 2005 (World Bank 2009). Another concept similar to the Eco-city in China is the Eco-garden City, first proposed in 2004 by the MoHURD, which is based on the idea of Garden City in 1992. However, the standards of guidance and evaluations focus more on the construction of urban infrastructure. The Eco-city plan stresses the eco-environment of the city, but the Eco-garden city program places more emphasis on the quality and coverage of cities' public infrastructure services and pollution control.

Between the local initiatives of Eco-city, China has witnessed another type of projects, collaborating with international partners, bringing their experiences and aimed at building eco-city at a larger scale. Recent eco-city projects that have received international attention included Sino-Singapore Tianjin Eco-city, Tangshan Bay Eco-city, and Shenzhen Guangming New District (Yu 2014). These projects led by the central, provincial, or municipal governments are often notable, therefore attracting much attention from the public and private sectors. The report from Chinese Society for Urban Studies (2011) showed that around 600 cities across China have planned to develop eco-city.

2.4.5 Low-carbon city

Chinese scholars introduced the concept of a low carbon city based on the low carbon economy (Department of Trade and Industry 2003), low carbon society (Ashina et al. 2012) and low –carbon lifestyles, etc. to reflect the issue of climatic change challenges. These concepts must be the reference to direct the future urban development in China (Liu et al. 2009a).

The World Wide Fund for Nature (WWF), formerly named the World Wildlife Fund, initiated a project called low carbon city initiative in China in 2007 to explore a new way of urban development as the government plans to decrease energy intensity. Low carbon city initiatives will explore low carbon development models in different cities, attach importance on improving building energy efficiency in construction and transport sectors and addressing the development of renewable energy. Baoding and Shanghai were selected as the first stage of pilots (WWF 2007).

NDRC (2010) formally proposed the low-carbon city in China and launched the national pilots of the first five low-carbon provinces and eight low-carbon cities. Two years later, another one low-carbon province and twenty-eight low-carbon cities were planned. These national low-carbon cities are listed in Table 2.2.

Table 2.2 National low-carbon city/province pilots proposed by NDRC
Source: Zhou (2015)

Year	Low-carbon City/Province	National Low-Carbon Pilots
2010	Low-Carbon Province (Total of 5)	Guangdong, Liaoning, Hubei, Shanxi and Yunnan
	Low-Carbon City (Total of 8)	Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang and Baoding
2012	Low-Carbon Province (Total of 1)	Hainan
	Low-Carbon City (Total of 28)	Beijing, Shanghai, Shijiazhuang, Qinhuangdao, Jincheng, Hulunbeier, Jilin, Daxinganling, Suzhou, Huaian, Zhenjiang, Ningbo, Wenzhou, Chizhou, Nanping, Jingdezhen, Ganzhou, Qingdao, Jiyuan, Wuhan, Guangzhou, Guilin, Guangyuan, Zunyi, Kunming, Yanan, Jinchang and Wulumuqi

The low carbon concept could be the reaction to the issues of China’s carbon dioxide emissions. In fact, the low-carbon city is a relatively newer concept than the eco-city and extensively used at the international level. The goal is to tackle the issue of global climate warming, reduce carbon emission intensity, and promote green economic development. However, the NDRC has neither provided a precise definition for a low carbon city nor recommended specific guidance and methods on how to compile a low carbon city development. As a result, many scholars attempt to define the concept and develop evaluation methodologies in worldwide (Li et al. 2012; Price et al. 2013), but the definition of a low-carbon city is similarly vague because there is no comparable benchmark for all countries. Table 2.3 is the action plan of the first eight low-carbon pilots.

Table 2.3 The first eight low-carbon pilot cities plan by NDRC
Sources: Zhou (2014); Zhou (2015)

City	Low-Carbon Action Plan	Relevant Documents
Baoding	Reduce 35% CO_2 emission intensity by 2020 compared to 2010;	"Opinion on Constructing Low Carbon City(draft)," 2008;"Baoding Low Carbon City Development Plan,"December 2008
Guiyang	Reduce 40% energy consumption per unit of GDP and 40% CO_2 intensity by 2020 compared to 2005;	"Guiyang city low carbon development action plan framework", July 2010
Nanchang	Reduce 38% CO_2 intensity by 2015 compared to 2005, and 45-48% by 2020;	"The action plan for Nanchang low carbon pilot city", November 2011
Chongqing	Reduce 40% CO_2 emission intensity by 2020 compared to 2005;	"Chongqing Low Carbon Transformation Research: Case Study in Chemical, Automobile and Energy Industries," 2010

Hangzhou	Reduce 50% CO_2 emission intensity by 2020 compared to 2005;	"Implemented opinion on the construction of low-carbon city," December 2009.
Shenzhen	Reduce 39% CO_2 emission intensity by 2015 and 45% by 2020 compared to 2005;	"Middle- and Long-term Plan for Shenzhen low carbon development," February 2012
Tianjin	Reduce 15% CO_2 emission intensity by 2015 compared to 2010, and 45% 2020 compared to 2005;	"Tianjin Climate Change Program," March 2010
Xiamen	Reduce 40% energy consumption per unit of GDP by 2020 compared to 2005;	"Xiamen Low Carbon Development Master Plan," January 2010.

2.4.6 Low-carbon Eco-city

In 2007, the environmental issues were reported at the 17th National Congress of the Chinese Communist Party for the first time. Since then, there is a broad range of discussions about eco-civilisation implementation at the different level of governments, mass media, academia, etc. In 2009, MoHURD formally issued the idea of low-carbon eco-city under this context. Low-carbon eco-city, a much newer concept that combines low-carbon and eco-city concepts, has been emerging in China (Qiu 2009). Low-carbon eco-city concept came from the idea of "eco-civilisation". The concept has recognised an extension of the low-carbon city, adding features of harmony between human beings and the natural environment; it is highly supported at official level in China and is viewed as the future direction of China's economy and urban development, which can be consolidated in the 12th-Five-Year Plan (Liu 2014).

In 2009, the Chinese Society for Urban Studies released the Chinese low carbon eco-city development strategy, which discusses techniques and policies to promote low-carbon development (Chinese Society for Urban Studies 2009). It shows that the low carbon eco-city has placed more emphasis on energy efficiency, carbon dioxide emissions mitigation and environment conservation (ibid.). The central government makes effects define the concept, theoretical framework and carry out some pilot projects. In 2010, MoHURD launched national low-carbon eco-city program in Shenzhen and Wuxi. Three years later, MoHURD launched international low-carbon eco-city program pilots collaborating with the US in Langfang, Weifang, Rizhao, Hebi, Jiyuan and Hefei. These pilot projects aimed to explore pathways of low-carbon transition and reduce energy consumption, as leadership in low-carbon eco-city development (Zhou 2015).

2.4.7 Green theories summary

The above sessions discuss the evolution of ecological theories development in China. This part will summarise relevant, important concepts of green theories from both international (Table 2.4) and domestic level (Table 2.5). Points like the definitions of selected critical theories, the major contents, indicators and their concerns will be summarised.

Table 2.4 Popular relevant theories development in the world
Source: Adapted and reorganised from Zhou (2014); Khanna et al. (2013)

Concept of theory	Background, Definition, and Major Content	Aims and focus

Garden City	Initiated by Howard in 1898, Garden cities were intended to be planned, self-contained communities surrounded by "greenbelts"(parks) and containing areas of residences, industry, and agriculture.	Supports the building of cities that optimise parks and green spaces.
Sustainable City	This concept calls for considering the planning into the operation of cities. The concept is that “it meets the needs of the present without compromising the ability of future generations to respond to their needs” (Brundtland 1987, P16) Speech at the opening of the UNESCO International Conference on: “Culture for Sustainable Cities” (Kumaresh 2015)	Focus on natural environment and built environment, including energy, industry, as well as human settlements “Cities are engines of economic growth, social prosperity and environmental sustainability. Culture is at the heart of this prosperity”.
Livable City	Stresses on the quality of life in cities. The living standards refer to the level of wealth, comfort, material goods, and necessities available to the socioeconomic classes in a city.	Focuses on living standard and the quality of urban development
Eco-city	Ecological cities enhance the well-being of citizens and society through integrated urban planning and management that harness benefits of ecological systems, protects and nurtures assets for future generations (Khanna et al. 2013, P650).	Achieve higher economic development with least resource and environment cost. Also, the ultimate aim is to achieve socially, economically and environmentally sustainable development.

Low-carbon city	Low-carbon cities separate economic growth from the use of fossil fuel resources, and it should rely on renewable energy, energy efficiency, and green transport.	This concept raises an awareness of carbon dioxide emissions and climate change to city development.

The main reason that so many concepts emerged in China is that different government departments have different responsibilities. Specifically, MEP focuses primarily on the environmental aspects, while MoHURD attaches great importance to the urban development of the city, such as the built environment and infrastructure construction. NDRC should be responsible for drawing up some policies to battle against climatic change, reduce carbon emission intensity, and promote green economic development. General, there are certain overlaps between the functions of these different departments, but they are essentially responsible for their fields by issuing various standards and guidelines. The different concepts differ in focus, but environmental protection has always been a paramount aspect. For example, the green city and national garden city focus heavily on the landscape and green space coverage, whereas the low-carbon city focuses more on GHGs reduction. However, what is the relationship between low carbon city and eco-city? First, the core ideology is consistent: both focus on the ecological and environmental issues. On the other hand, there are also some differences. The eco-city concerned the natural and built environment with human beings. Conversely, global climate change is the main target of the low-carbon city. As a result, the content of eco-city is much broader and comprehensive, while low-carbon city particularly emphasises on the reduction of carbon dioxide emissions and increase carbon sequestration. To some extent, the low-carbon city is a degree of a subset of the eco-city. The low-carbon eco-city proposed in China is a combination of low –carbon city and eco-city. Table 2.5 describes and compares the differences between the green concept from China.

Table 2.5 Popular relevant theories development in China

Source: Reorganised from Liu et al. (2014)

Concept	*Proposed Date*	*Proposed organisations*	*Concerned aspects*				
			Carbon-efficient economy	*Environmental protection*	*Energy efficiency*	*Economic growth*	*Social aspects*
Green City	*1970s*			✓		✓	✓
National Garden City	*2000*	*MoHURD*		✓			
Eco-demonstration Communities	*1995*	*MEP*		✓		✓	✓
National Environmental Protection Model City	*1997*	*MEP*		✓		✓	
Eco-counties *Eco-city* *Eco-province*	*2003*	*MEP*		✓		✓	✓
Eco-Garden City	*2004*	*MoHURD*		✓			
Low-carbon City	*2010*	*NDRC*	✓		✓	✓	
Low-carbon Eco-city	*2010*	*MoHURD*	✓	✓	✓	✓	✓

2.4.8 Practical projects in China and worldwide

Due to the environmental consequences of global warming and unavoidable climate change, urban planners and designers have placed greater emphasis on energy conservation and carbon emission reduction (Ballarini and Corrado 2009). Many organisations and municipalities around the world have set low carbon goals for 2020 (Gomi et al. 2010). Furthermore, more than 500 of the international coalition for local environmental initiatives have established GHGs baselines and benchmarks and have carried out some projects (Hoornweg et al. 2011). For example, the Low carbon cities programme in the UK was supported by the carbon trust. Bristol, Leeds, and Manchester were selected as the pilot projects to assist them to develop city-wide strategies for reducing carbon dioxide emissions across city regions (Carbon trust [no date]). Another example is Masdar City in the United Arab Emirates where it is aimed for its zero waste, zero carbon and fossil fuel free city (Reiche 2010). Because of limited resources and environmental capacity at national and international levels, the Chinese government and some organisations jointly launched a series of programmes named "low carbon city initiative in China" to explore new ways for low carbon development in urban areas to protect people and nature from dangerous environmental threats (WWF 2007). This initiative will explore low carbon development models in different cities, improve energy efficiency in construction and transport sectors, and then other cities in China can learn from these successful experiences and replicate them in practical projects. For example, Shanghai and Baoding were selected and became the low-carbon cooperative pilot cities in the first stage. The objective of this initiative in Shanghai is to focus on:

- Policy research on eco-building promotion on ecological building development to reduce residents living carbon dioxide emissions
- Energy efficiency improvement of existing large-scale public buildings, strategies include to promote energy consumption management, auditing and retrofitting, energy efficient operation, and international cooperation
- Launch energy-saving campaign to raise public awareness of energy efficiency.

For Baoding city, the target is to attach greater importance to the field of:

- New energy and renewable energy industry development including information database and service platform on renewable energy, technology exchange, and training

- Comprehensive application of new energy and energy-saving measures and explore the low carbon model city development including policy research on promotion of the renewable energy development.
- Low carbon city development-oriented planning including design and implementation and development of certification service and public technology platforms

For some other projects, Sino-Singapore Tianjin Eco-city (Baeumler et al. 2009), Tangshan Bay Eco-city (Ma 2009) and Guangming Low-Carbon New Town in Shenzhen (Yu 2014) have showed more comprehensive plans, which cover advanced transport systems, renewable energy applications, innovative passive design strategies, and advanced public infrastructure systems (Cales 2014). However, Liu (2010) argued that low carbon cities in China are "high carbon" per capita in fact, with many places in China adopting this label in reality.

（1）Pilot projects in China

- Sino-Singapore Tianjin Eco-city (SSTEC)

The Sino-Singapore Tianjin Eco-city (SSTEC) is located within the Tianjin Binhai New Area (Fig. 2.5). SSTEC is scheduled as a compact city, and a good mix of land uses, including public amenities and commercial facilities are located close to residential areas, similar to how new towns are planned in Singapore (SSTEC 2009; Wikipedia 2015). This project has received much attention by the central government due to the target of becoming a model pilot of eco-city replicated by other cities in China (Baeumler 2009). Many implementations are conducted in this project, including:

(1) Integrating land use plans and corresponding detailed transport planning into supporting green trips based on Transit-Oriented Development (TOD) principles;

(2) Developing its greening building standards and these standards are more advanced than the national or provincial levels and hope to set a new benchmark for China;

(3) Utilising technologies to promote new urban development towards sustainability and guarantee that these new urban developments provide a comfortable living and working environment.

Figure 2.5 SSTEC
Source: http://www.kepcorp.com/en/news_item.aspx?sid=2045

The China Academy of Urban Planning and Design, the Tianjin Institute of Urban Planning and Design, and the Singapore planning team jointly developed Master Plan of SSTEC. In the planning of the Tianjin Eco-city, one of the main guiding principles was to adopt an approach towards creating and designing a livable, efficient compact and green transport city, which would be developed ecologically. The planning focuses on the development of Key Performance Indicators (KPIs) jointly formulated by experts from Singapore and China, covering its environmental, economic and social development to confirm the effective coordination and monitoring (Sino-Singapore Tianjin Eco-city Administrative Committee, 2008). The Master Plan can be summarised as "One Axis – Three Centres – Four Districts"(SSTEC 2009). (Fig. 2.6 illustrates)

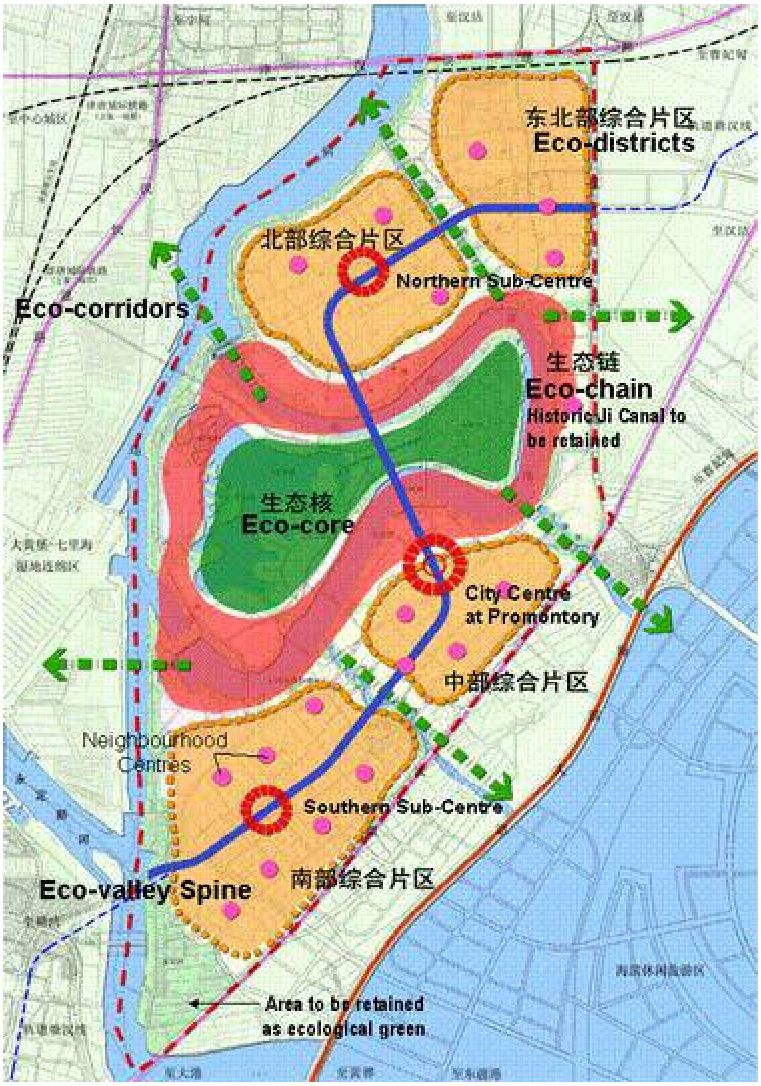


Figure 2.6 Masterplan overview of SSTEC
Source: http://www.tianjinecocity.gov.sg/bg_masterplan.htm

To create an eco-city model, the Master Plan of SSEC outlined the following strategies for green development (Li et al. 2012, p.13):

- Promote energy savings in transport and buildings

- Raise public awareness of energy efficiency
- Consolidate industrial energy savings
- Support the clean energy industry
- Promote the "circular economy" model
- Consolidate eco-agriculture
- Consolidate forestry management

However, "SSTEC has ambitiously tackled the technological side, but without adequate education of the public, the full potential of green technologies will not be fulfilled. Some resources to be spent on public education remain uncertain" (Li et al. 2012, p.15). In addition, the codes of constructing green buildings are higher than that of conventional buildings, but the information on construction costs is limited, developers may have less incentive to engage in green development.

- Tangshan Bay Eco-city

A new environmentally-friendly city is situated in the Tangshan region 250 kilometres East of Beijing, which is supported by Chinese and Swedish organisations initiated in 2007. Beijing Capital Steel Group Corporation, SWECO from Sweden and Qinghua Urban Planning and Design Institute were appointed to complete the feasibility study and detailed Master Plan for Tangshan Bay Eco-city, using innovative examples from Malmö as a source of inspiration shown in Fig. 2.7.

In the planning and design stage, sustainable development concepts and technologies are adopted. Tangshan Bay Eco-city adopt the strategy of land-use and green transport integration and advocate the city of short distance (Ma 2009). To achieve this goal, Tangshan Bay Eco-city was planned to be mixed land-use, which could guarantee the city to be a more compact city. Furthermore, the city was designed to be a transit-oriented development. Downtown and sub-centres were linked by public transport such as light rail systems (LRT) and bus rapid transit (BRT). By these methods, people will heavily rely on transit, avoid unnecessary travel, and thus reduce trip distances. Therefore, the city will be the least land and fuel consumptions. For the road system plan, the city adopts European road pattern, which features narrow, dense road network, and restriction of car-use. The city will be a short distance, transit-oriented and pedestrian-friendly development.

Figure 2.7 Master planning overview of Tangshan bay eco-city
Source: http://www.sweco.se/sv/Sweden/Nyheter/2011/Sweco-utvecklar-ny-del-av-eko-stad-i-Kina/

- Guangming Low- carbon eco-city New Town, Shenzhen

Guangming low-carbon eco-city new town is in Bao'an district of the north-west of Shenzhen (Fig. 2.8). The planning of Guangming New Town is to develop a low- carbon city. The measures include a convenient public transport network and a slow -traffic system, compact and TOD strategy. Apart from these, a series of green technologies were conducted integrated with urban development, including the ideas of green transport, green building, green community, and green space to reduce carbon dioxide emissions (International New Town Institute 2015).

Figure 2.8 Planning of Guangming low- carbon eco-city new district in Shenzhen
Source: Google image

For green transport, it focuses on (Energy Smart Communities Initiative 2014):

• Walkable pavement, bike lane system.

• Slow transport system and bus-oriented development strategy.

For green buildings, it attaches great importance to the application of green building technology, such as solar power lighting system and hot water system (Energy Smart Communities Initiative 2014).

A brief introduction and summary of the above three typical examples of low carbon transport planning for low carbon city development is presented in Table 2.6.

Table 2.6 Three examples comparison in low carbon transport planning

Source: Compiled from (Li 2012; Yu 2014; Liu 2014)

Name	Brief Introduction	Characteristics of low carbon transport
Sino-Singapore Tianjin Eco-city	Located within the scope of Tianjin Binhai New Area, with a total area of approximately 31.23 km^2	Promoting transport model development dominated by a green low-carbon transport system; Closely integrated with land use, improve the percentage of public transport, reduce car dependence, and create transport modes of low energy consumption, slow transport system.
Tangshan Bay Eco-city	In Tangshan region 250-kilometre East of Beijing with the total planning area of about 150km^2	Integration the eco-city development goals and green low-carbon transport systems overall scheme; Integration transport and land use patterns; give priority to the development of urban public transport, walking system and highlight the importance of bicycle system, build a walkable city.
Guangming New Town, Shenzhen	Situated in the north-west of Shenzhen in Bao district, Created in 2007, with the total area of 156.1 km^2	Establish BRT service system, integrate neighbourhood and form an excellent environment for walking, develop bike lane system using the Network-like regional green space system.

From these three typical examples, the low carbon new urban development in China has similar features shown in the followings:

(1) Establish public transport as the backbone of the urban transport system to limit car travel. (2) Integrate land use with mix and intensive development, optimise block and construct different roads to form a slow transport system and encourage low-carbon travel. (3) Strengthen public transit linkage and eliminate car dependence on short trips. Figure 2.9 summarises and compares the low-carbon planning and general planning.

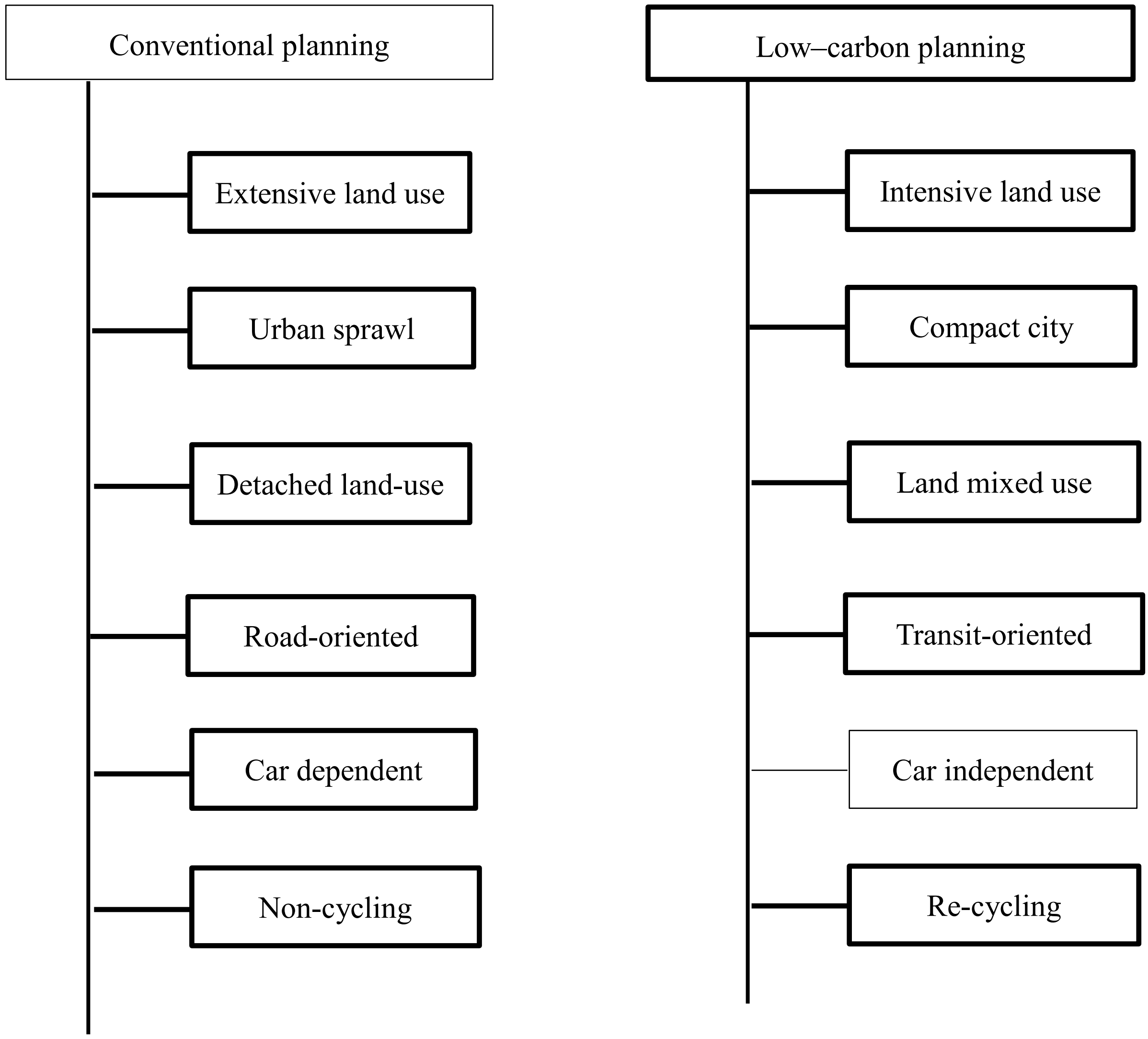


Figure 2.9 Comparison of traditional planning and low-carbon planning

Source: Ma (2009)

(2) Typical worldwide projects

Around the world, cities are implemented low-carbon development. The experience of Masdar, Freiburg, and Curitiba are selected as examples in this research.

- Masdar City

The Masdar city, a carbon-neutral, zero-waste urban community in Abu Dhabi, is one of sustainable mixed-use development designed projects (Fig. 2.10). On its completion, it would become one of the first aimings toward a zero-carbon, sustainable settlement project (Nader 2009).

Figure 2.10 Masdar city planning
Source: http://www.fosterandpartners.com/media/Projects/1515/img0.jpg

The design of community uses strategies (a mixed-use, low-rise, and high-density development). Buildings are grouped close together to create narrow streets, and it means more shades and low temperature in the streets so that people can walk with a comfortable feeling. Moreover, the wind tower constructed sucks air from above and pushes a cooling breeze through streets.

For the transport sector, the initial design banned automobiles. Travelling in the city are mainly by public transport systems with existing road and railways connecting to other locations outside the city. Masdar City is intended to make do entirely without fossil fuel use. For its energy needs, it was also to rely exclusively on a mix of renewable sources including solar thermal, photovoltaic, and wind (Janajreh et al. 2013). The majority of private vehicles will be restricted to parking lots along the city's perimeter.

- Freiburg, Germany

The German city of Freiburg is well-known as one of the top low carbon cities in the world. Freiburg, a typical compact city with strong neighbourhood centres where people's needs are within walking distance, has successfully adopted TOD (Gregory 2011). At the same time, renewable energies are applied in this city. For example, energy-saving houses are quite common compared to other cities in Germany, as it is well- known for its efforts in various initiatives to promote the installation of solar energy systems (Fig. 2.11).

Freiburg's success can be found in its citizen's participation and the city's comprehensive policies aiming at sustainability. Firstly, leading research institutes of solar technologies are based in Freiburg, as well as small and medium-sized companies promote and application renewable energies. Secondly, the city's policies and actions have included carbon emission reduction. For example, the local administrative devised the first low carbon traffic plan, aiming to improve the mobility while reducing traffic. Moreover, the government always steadily expanded the public transit network (Gregory 2011). Thirdly, to improve energy efficiency in existing buildings, the city has a support program for housing insulation and energy retrofits. Moreover, it requires that all new homes built on city must meet a new low-energy efficiency design standard. Finally, cycling is encouraged. The city administration has developed over 400 km of cycle paths (ibid.).

Figure 2.11 Solar settlement in Freiburg
Source: http://ais.badische-zeitung.de/piece/00/e4/ec/2e/15002670.jpg

- Curitiba, Brazil

The city of Curitiba, Brazil, has gained international acclaim for its planning initiatives. Curitiba’s Master Planning integrated transport with land use planning. It limited central area growth while encouraging commercial growth along the transport arteries radiating out from the city centre. Curitiba has transformed itself into a model of the low-carbon city through its innovative public transport system coupled with land use policy.

The city is bus rapid transit (BRT) oriented shown in Fig. 2.12. Everyone is easy to access to the public transport, and the five top routes from the city centre to the suburban area are used as “ growth corridors” in the city. Curitiba's BRT satisfies 80% of the daily trips resulting in 25% lower carbon dioxide emissions per capita than the average cities. The advantage of BRT is efficiency: its ability to move people around the city quickly, thus reducing dependency on automobile use (Magalhaes and Durán-Ortiz 2009).

Figure 2.12 BRT in Curitiba

Source: http://upload.wikimedia.org/wikipedia/commons/2/2a/Bus_Stops_3_curitiba_brasil.jpg

2.5 Review energy consumption on buildings and road transport sector

Buildings and the transport are a significant contributor to energy use and CO_2 emissions. China's building stocks are characterised by rapid new construction and demolition of old buildings, and large-scale urban expansion. Section 2.5.1 reviews the situation of Chinese building energy consumption and its associated factors that affect energy consumption. Section 2.5.2 reviews current carbon dioxide emissions in road transport sector from China and the worldwide.

2.5.1 Building sector energy consumption

The increased urbanisation rate in China has dramatically affected the number of buildings in cities with major effects on the energy consumption (Santamouris et al. 2001). Energy demand from building sector will increase dramatically in cities, as an estimated another 300 million people will move to cities over the next 20 years in China

(Baeumler et al. 2012). Therefore, energy-saving from buildings faces a significant challenge in China.

By the end of 2017, China's urbanisation rate has reached 58.5% and is projected to 75% by 2050 (Khanna et al. 2013; Chinese Society for Urban Studies 2011; Zhang 2015). More urban infrastructure and services will be needed to satisfy the demands of future city residents, resulting in higher energy consumption and associated carbon dioxide emissions.

Energy consumption and associated carbon dioxide emission in cities mainly come from buildings and the transport. The global contribution from building energy consumption has steadily increased in developed countries and has exceeded the transport sector (Steemers 2003). Current predictions show that this upward trend will continue (Pérez-Lombard et al. 2008). Energy use from most developing countries will grow at an average annual rate of 3.2% and will exceed the developed countries (North America, Western Europe, Japan, Australia and New Zealand) at an average growth rate of 1.1% by 2020 (ibid.). For example, 37% of direct fuel consumption in buildings occurs in urban areas in the USA (Parshall et al. 2010). This figure in the UK is 28%, well above the Spanish 15% mainly due to a more severe climate and building type (Pérez-Lombard et al. 2008).

Climatic conditions are a basic factor that affects building energy consumption. There is a vast territory in China, and it is impossible to design a single building code for the whole country. The climatic zones consist of five parts relating to severe cold zone, cold zone, temperate zone, hot summer and cold winter zone, and hot summer and warm winter zone, as shown in Fig. 2.13.

Figure 2.13 Five-climate zone distribution in China.

Source: http://1t2src2grpd01c037d42usfb.wpengine.netdna-cdn.com/wp-content/uploads/sites/2/2014/08/China-climate-zone-map-628x531.png

Buildings in the north part of China is heated mostly by district heating systems as the severe weather conditions. In contrast, buildings in southern China requires small heating demand. However, annual building energy consumption (BEC) has been increasing at more than 10% over the past 20 years (Cai et al. 2009). According to the official report, the total floor area of residential buildings in China is about 40 billion m^2 by the end of the year 2013 (National Bureau of Statistics of China 2014). The overall national building energy consumption is 16 billion tons of standard coal, which accounts for 20.7% of the total end energy consumption (Jiang and Yang 2006). The current energy consumption from buildings in China can be divided into three main categories according to the locations and the areas—energy consumption in rural residential buildings, residential and public buildings in cities excepting for heating, and northern cities for heating— and this is presented in Table 2.7:

Table 2.7 The BEC categories in China

Source: Cai et al. (2009)

Items		Building area (billion m^2)	BEC (billion kWh/year)	BEC (kWh/m^2)
Rural residential buildings		24	89	7.5
Northern cities for heating		6.5	370	57
Cities excluded heating	Residential	10	200	10-30
	Conventional public buildings	5.5	160	20-60
	Large-scale public buildings	0.5	100	70-300
	Subtotal	16	460	29

Moreover, the energy consumption in large-scale public buildings is about ten times than that of residential buildings in China (Li and Yao 2009). For example, the floor area of large public buildings in Beijing only accounts for 5.4% of the city's total building floor area. However, its electrical energy demand is nearly equal to that of residential buildings (Liang et al. 2007). It is evident that these buildings have considerable opportunities for building energy saving. The survey (Jiang and Yang 2006) shows that annual energy consumption from large-scale public buildings in China had reached 100 billion kWh, which accounts for around 20% of the total national building energy consumption by the end of 2004. In contrast, the total floor area of these buildings was about 500 million m^2 that only consisted of less than 4% of the national urban building floor area (ibid.).

Apart from this, the BEC for heating in north China is also very high (Cai et al. 2009). This is because of the severe weather of north China, as well as the huge area of north China, accounting for 70% of the whole country. For example, the northern building floor area is about 6.5 billion m^2, and the building energy consumption for heating stands for 45% in the total national urban building energy consumption. Figure 2.14 shows the detailed information about the energy consumption of different building types and locations in China. Northern heating zones account for 36% of total energy consumption compared to other sectors.

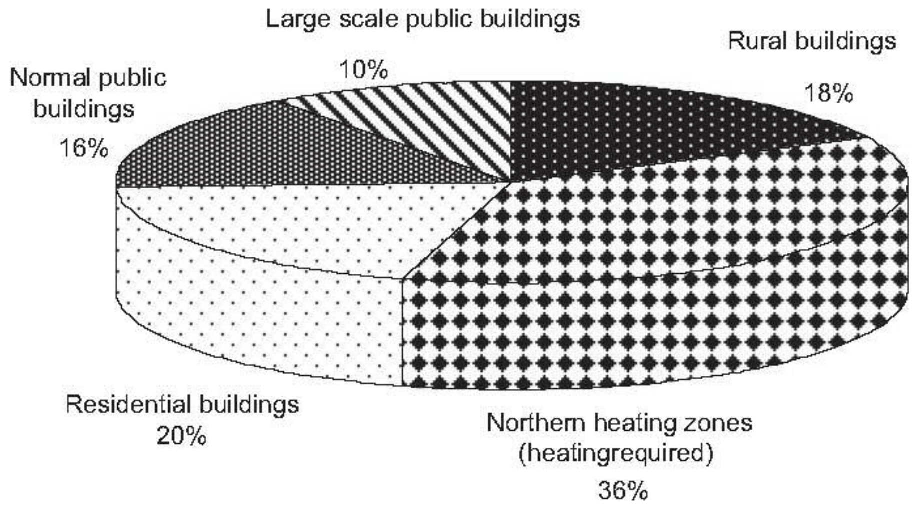


Figure 2.14 The BEC proportions of different building types in China
Source: Cai et al. (2009)

From the review of building energy consumption, which is a complicated issue influenced by both internal (weather conditions) and external factors (building floor area), it mainly focuses on two aspects as follows:

1) Northern space heating: space heating in the north part of China occupied most of the total energy consumption for urban buildings. This is primarily because of the climatic conditions, and large building floor area (Chmutina 2010).

2) Large-scale public buildings and residential buildings: a small percentage of public buildings consume a tremendous amount of total building energy. Larger public buildings are always with huge glass screen walls without any shading, and this can cause extra cooling demand in the summer period. Residential buildings have a significant energy consumption due to the large floor area caused by rapid

urbanisation in the cities.

2.5.2 Energy consumption on road transport sector

The transport sector is always the source of CO_2 emitters around the world. Over the last 30 years (1980 to 2010), its annual growth rate (especially for oil consumption) has reached over 2.6%, far greater than that of the residential sector (Wang et al. 2014). According to the report from the Institute of Energy Economics of Japan, the final energy consumption by China's transportation sector increased from 24.1 Mtoe (million tons of oil equivalent) in 1980 to 182 Mtoe in 2010. Moreover, the energy consumption in the transport sector is different from the development stage in each country. Figure 2.15 indicates the differences and describes the final energy consumption by the transport sector about total domestic energy consumption in three countries: China, Japan, and America. The bubble size represents the final energy consumption by transportation sector in these countries in the main years. The percentage of the vertical axis indicates the proportion of final energy consumed by transportation sector relative to total domestic final energy consumption. It has shown that the energy consumption in the transport sector in the U.S.A accounts for appropriately 40% of the total domestic energy consumption in 2010. Similarly, Japan's final energy consumption in transport sector accounts for about 25% of its total domestic energy consumption because of a smaller land area and higher population density. In contrast, China's per capita energy consumption by the transport sector is much below these two countries due to a large population, only 10%.

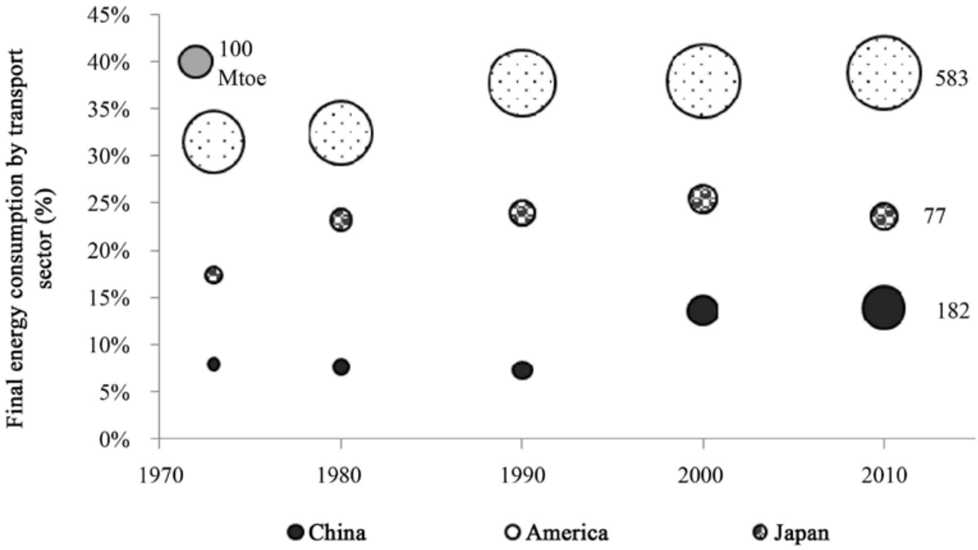


Figure 2.15 Proportion of final energy consumption by transport sector about total domestic energy consumption from three countries

Source: Wang et al. (2014)

Figure 2.16 represents the total amount (bubble size) of final energy consumption by transport sector in China, as well as its relative proportion to the total final world transport sector. It illustrates the total final energy used in the transport sector in China is increasing at an alarming rate from less than 2% in 1970 to about 8% in 2015, receiving the worldwide attention.

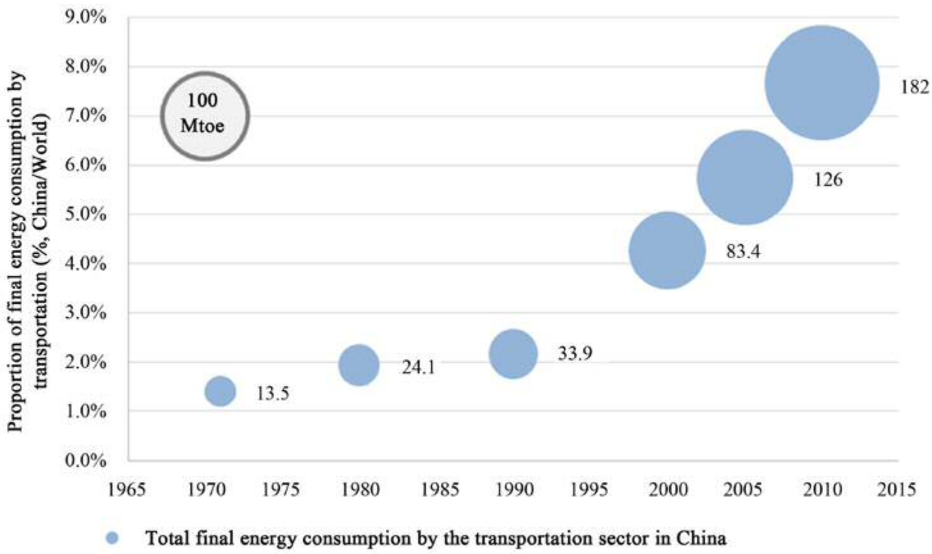


Figure 2.16 Total final energy consumption of China's transport sector and its proportion in the world's transport sector.

Source: Wang et al. (2014)

Over the next two decades, China will continue its rapid progress in the transport sector, and it will experience a period of rapid growth along with the booming economy and improving living standards (Wang et al. 2014). Many studies have explored in China's transport energy consumption. Yan and Crookes (2009) study the assessment of the effectiveness of possible measures for reducing energy consumption in China's road transport sector; Cai et al. (2006) analyse China's energy demand in future by identifying some key barriers which affect fuel consumption options in the road transport sector. Their research is mainly focused on the technological, financial and institutional aspects. The key issue for China is finding ways to develop low-carbon and efficient transport in the future.

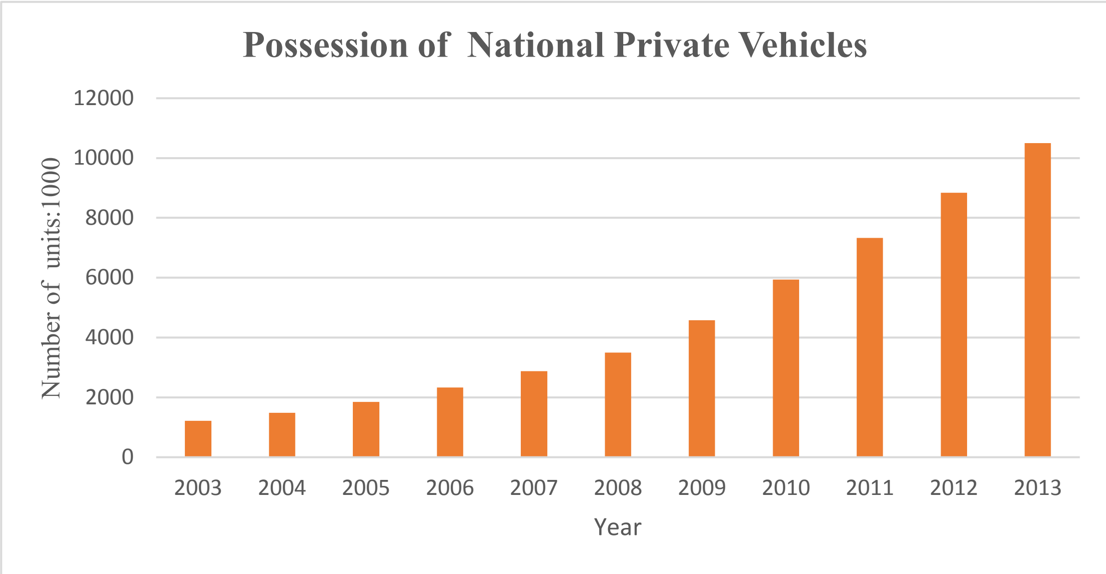


Figure 2.17 Possession of national private vehicles

Source: National Bureau of Statistics of China (2014)

However, there is a rising trend in the number of private vehicles shown in Fig. 2.17. This dramatic increase in China has resulted in the rapid growth of automobile fuel consumption, which has gradually become the largest source of CO_2 emissions. He et al. (2005) analyse the status of oil consumption on road transport in China and then predict the future trend of the oil demand and CO_2 emissions on road transport based on the three scenarios (Fig. 2.18 and Fig. 2.19 show). It shows that the oil demand and carbon dioxide emissions in China's road transport sector will increase dramatically even under the high-fuel economy improvement control.

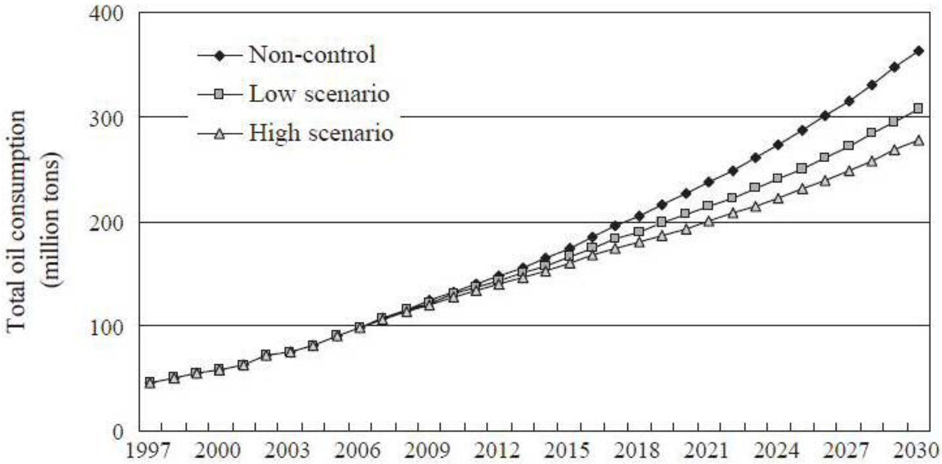


Figure 2.18 Oil consumption of China's on-road vehicles 1997-2030
Source: He et al. (2005)

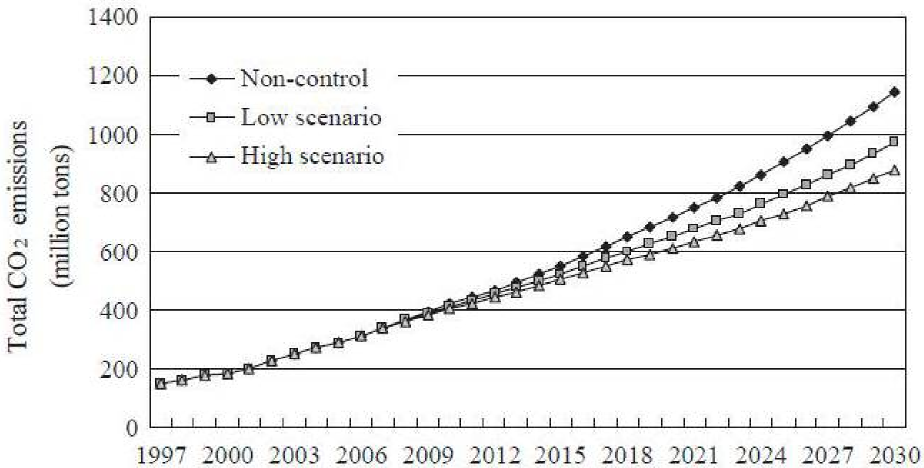


Figure 2.19 CO_2 emissions of China's on-road vehicles, 1997-2030.
Source: He et al. (2005)

Currently, the reduction of energy consumption and the alternative energy development are the two ways to reduce the transport-related CO_2 emissions in the transport sector. The first way focuses on improving the fuel consumption efficiency of vehicles or develop alternative fuels, while the second way is to develop appropriate planning to reduce unnecessary travel. In contrast, in some developed countries such as the U.S.A, the cars accounted for over 80% of the total transport energy consumption (He et al.

2005). This energy consumption in China remains at a relatively lower level and is still in its infancy. However, Hu et al. (2010) predict that for future oil consumption on road vehicles, the oil demand in 2030 might be 300-500 million tons, three times the present consumption. Moreover, many factors affect the transport-related energy use such as urbanisation rate and the improving living standards. The development of the road transport in China cannot follow the model of the U.S.A of increasing private car to improve people’s living standards. Instead, it is necessary for China to speed up the construction of the conventional transport system for energy saving. China needs to optimise further traffic structure and try to improve traffic technology and energy efficiency. This will fulfil the energy-saving potential based on infrastructural energy saving and accelerate the pace of China’s low-carbon transport sector.

2.6 Review major causative factors affecting energy consumption and carbon dioxide emissions in building and road transport sector at the macro level

Buildings and the transport, as essential components in the city, play a significant role in the energy consumption and carbon dioxide emissions. Building-related CO_2 emissions across the world have continued to rise by nearly 1% annually since 2010. Coal and oil used in buildings have remained constant since then, while natural gas use grew steadily by around 1% annually. Global use of electricity in buildings grew on average by 2.5% per year since 2010, and in non-OECD countries, it increased by nearly 6% per year (IEA 2017). Moreover, the transport sector accounts for nearly 25% of global energy-related CO_2 emissions (IEA 2009), and it is regarded as one of the increasing energy consumption and carbon dioxide emissions sources. The actual energy consumption from the transport sector in China accounts for 10% to 15% of the national total energy consumption (Wang et al. 2014). China needs to reduce its energy consumption and carbon emission to improve the country's environment, addressing the climate change issue. Thus, a better understanding of urban energy consumption is necessary for decision-makers to control urban carbon dioxide emissions and local pollution issues at various levels of urbanisation.

This session reviews the basic questions: what primary factors contribute to energy usage and CO_2 emissions in buildings and road transport sectors at the macro-level in urban areas. Many previous studies have shown that urban geography, building design, systems efficiency, occupant behaviour on building energy consumption, and the technology improvement, transport planning and management on transport carbon dioxide emissions (Bruff and Wood 2000; Ratti et al. 2005). This section reviews factors from macro-level including policies (urban planning policies, energy efficiency standards, and transport policies), urban form, urban design, accessibility, renewable energy applications, and finally urban heat island effect (UHI).

2.6.1 National policies for energy saving on buildings and road transport sector

(1) National urban planning policies for city development

Increasing urbanisation is a national policy priority in China, where decision-makers have understood the urbanisation as a necessary and efficient approach to promoting economic growth. Significant policies are usually formulated at the central level and conducted by provincial or municipal governments. A better understanding of energy consumption in urban areas will help the central government to set up national frameworks and to address urban development issues, such as climate change. In addition, land utilisation and transport planning policy to reduce carbon dioxide emissions is dependent on the urban form, location, density, and design (Owens 1992; Banister et al. 1997; Capello et al. 1999). Governmental guidance for reducing energy demand in urban areas suggest that measures should be taken on the urban form, including land mixed-use and intensive development, the need of vehicle travel reduction, and energy-saving in design by either standards of energy efficiency or the extensive applications of renewable energy technologies in design (Bulkeley and Betsill 2005). Table 2.8 illustrates approaches to reducing the urban energy consumption and presents relevant examples.

Table 2.8 National planning guidance relating to urban energy consumption
Source: Bulkeley and Betsill (2005)

Approaches to addressing urban energy use	Examples of national planning policy guidance
Reduce travel demand	Promote TOD and mixed land use
Reduce the number and length of travel activities	Focus on public transport links; promote public transport development, better design for the cycle and walking access; limit land use for roads and parking
Design for energy-saving	Take full advantage of the passive solar energy in the design stage; formulate energy-saving standards for buildings in design guidance
Renewable energy applications	Promote the renewable energy uses

On the other hand, there is a fundamental policy that the land-use policy can change the level of energy consumption as it influences modes choices and the degree of trip efficiency (Mindali et al. 2004). Specifically, it can affect three aspects:

- Intensification of land-use densities in cities
- Shifts in the mix land-use
- The combination of the intensification and mixed land-use, commonly known as the compact urban form.

Figure 2.20 illustrates the correlation between the land use policy and the level of transport-related energy consumption.

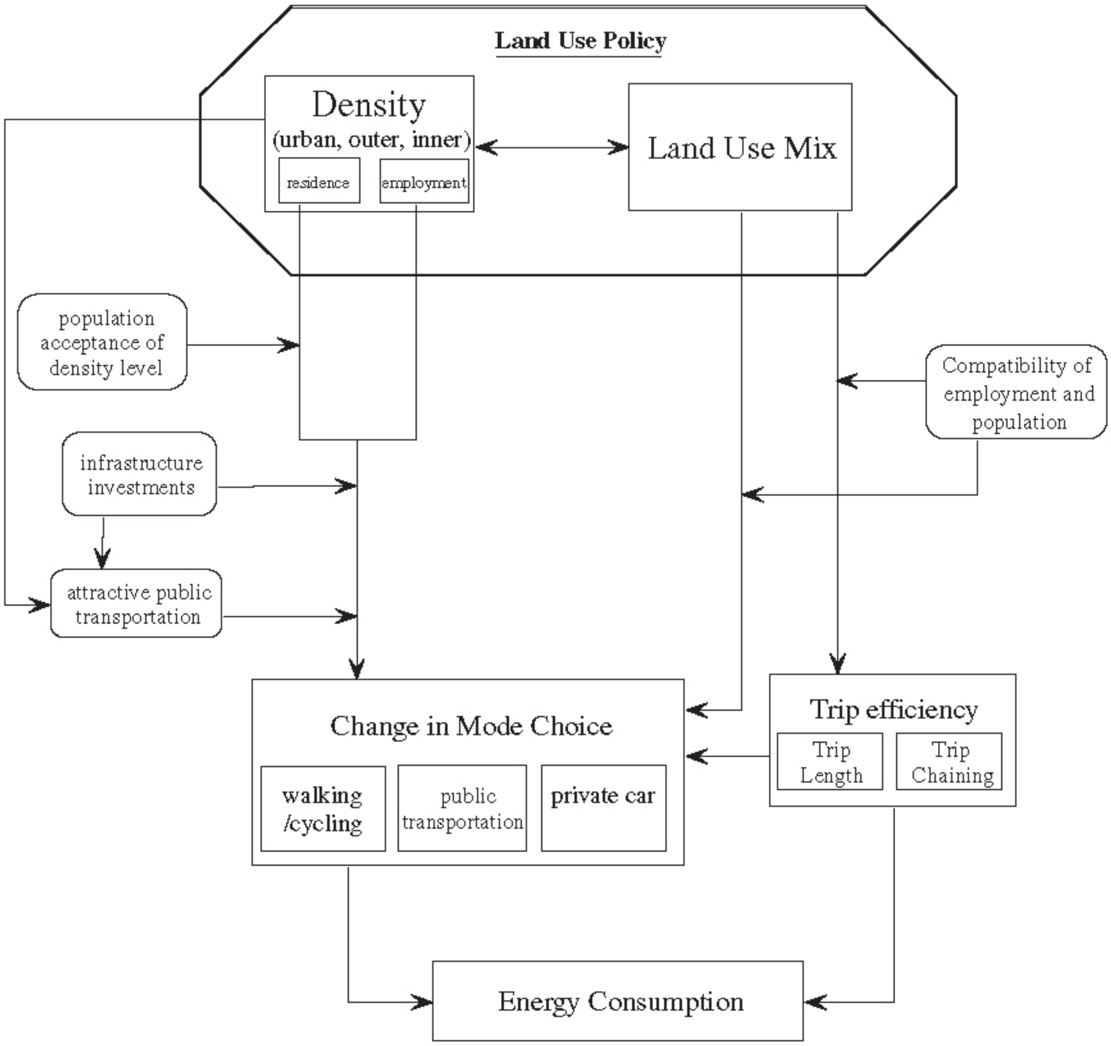


Figure 2.20 The process of land-use policy influences energy consumption by transport
Source: Mindali et al. (2004).

The land use policy can affect land use mix and densities. On the one hand, the density affects modal splits via infrastructure and public transport investments. One the other hand, land use mix also affects the travel mode and trip efficiency via compatibility of employment and population. And finally, the transport energy consumption is affected by travel modes and trip efficiency.

(2) National building energy efficiency standards and regulations in China

Energy efficiency standards for buildings are the tools for policy enforcement. There are two different national building energy standards in China: one for residential and another for commercial buildings. The common target of these standards is to reduce energy consumption as well as carbon dioxide emissions, but the standards are obsolete compared to the international level, and most are less stringent than EU counterparts. Moreover, these standards are rather narrow in scope and lack a strong framework to strengthen energy efficiency in construction (Yao et al. 2005). Worse still, the biggest problem of the energy efficiency standards is the unwillingness of local governments to implement specific regulations or to carry out national laws through supervision and penalties. Local governments placed more emphasis on the speed of construction, but this has resulted in the wasteful construction of the buildings (Andrews-Speed 2009). In addition, construction companies are in a shortage of guidelines and training for energy efficiency in the construction stage, and even with an inappropriate design (Yao et al. 2005).

Based on this context, the central government formulates the following framework of standards announced and implemented since 2004.

- **Introduction to "Design Standard for Energy Efficiency of Public Buildings" GB50189-2005**

The MoHURD released the standards of China's "public buildings" in 2005 in order to improve the energy efficiency of non-residential buildings (e.g.,commercial, educational, and governmental buildings), covering to five Chinese climatic zones.

The first standard (Energy Conservation Design Standard for Building Envelope and Air Conditioning) for non-residential buildings in China focusing on energy efficiency was issued in 1993 for tourist hotels. The current standard was updated and widen its scope to all public buildings in 2005 (GB50189-2005). The standards aim to reduce total energy consumption by 50% compared to the 1980s' buildings level. The standard corporates initiatives to improve energy efficiency, including natural ventilation and solar shading considerations, and control requirements for HVAC systems (GBPN 2013).

Although the standards play a significant role in the development of energy efficiency in commercial buildings, the enforcement of the standards is still a problem, especially in small and medium-sized cities due to a lack of awareness from the public and local governmental support.

- **The Chinese Green Building Standards**

The concept of green building was introduced into China in the 1990s (Xiao and Qiao 2009). According to green building evaluation standard (GBES) in China, green buildings are defined as "buildings which can save a maximum amount of resources featured by energy, land, water, and materials, protect the environment, reduce pollution, provide healthy, comfortable, and efficient space for people, and exist in harmony with nature (Li 2012, p.9)". Compared with the developed countries, the Chinese standards on the green buildings were launched much later. The whole development progress can be categorised into three stages, and the quality has been gradually improved.

- First Stage: Released China's Eco-House Technical Evaluation Handbook
- Second Stage: Released Green Building Assessment System for Beijing Olympic (2002)
- Third Stage: Released National Green Buildings Evaluation Standard (GB/T 50378–2006)

Although building energy consumption can be reduced to some degree through the development of green building standards, there are still some disadvantages. For example, they are "lack of indicators on responding to climate change", "lack of quantitative indicators", "higher costs for receiving certification" and "lack applying innovative green technologies" (Geng et al. 2012).

(3) National policies on road transport for carbon dioxide emissions reduction

Road transport in cities is responsible for the huge amount of CO_2 emissions. This is because, on the one hand, cities have been expanding urban areas continuously, and different cities from various provinces tend to interact with each other more frequently than before; thus population mobility is always increasing and contributes to more CO_2 emissions. On the other hand, the growing land use in cities has contributed to the conversion of buildings, and then it causes an increase in building energy consumption in cities. Meanwhile, the diversity of transport modes and the increasing vehicles in every year makes it more complex for passengers to transfer to different vehicles. Finally, with the development of the society, people have set higher standards for the comfort level and convenience of a trip.

Based on the above context, to reduce road transport energy consumption, the central government has issued various policy documents for public transport priority such as Energy Law (2007). It views transport energy conservation as optimising transport structure, giving priority to public transport development, enhancing the transport organisation and administrative ability, as well as improving the energy utilisation efficiency of traffic facilities. Public transport can provide a level of urban mobility similar to that offered by a private car, but it requires less energy and space per passenger-kilometre travel (PKT) (Figueroa et al. 2014) significantly. Moreover, public transport use can contribute not only to reducing energy consumption and emissions but also to congestion level, which improves traffic flows and reduces travel times. The provision of high-capacity and reliability of public transport infrastructure and services and the physical integration of walking and cycling facilities are critical to realising the less energy consumption in the transport sector. In fact, the Energy Law has guided significance on the transport energy saving. A reliable and affordable public transport system is a fundamental element of the low carbon transport system.

2.6.2 Urban form and urban energy

Theoretical definitions of the urban form indicate the importance of the interplay between social norms, business activity, and mobility (Race 2013). Many scholars believe that urban density can interpret urban forms, such as residential and employment density, mixed land-use, public transport supply, and commuting distance (Williams 2000; Holden and Norland 2005). Anderson et al. (1996) define urban form as the spatial configuration of fixed elements in the city, including the spatial pattern of land uses and their density, as well as the spatial design of transport and infrastructure. Moreover, they propose three different archetypal urban forms: the concentric form, radial form, and multinucleated form shown in Fig. 2.21.

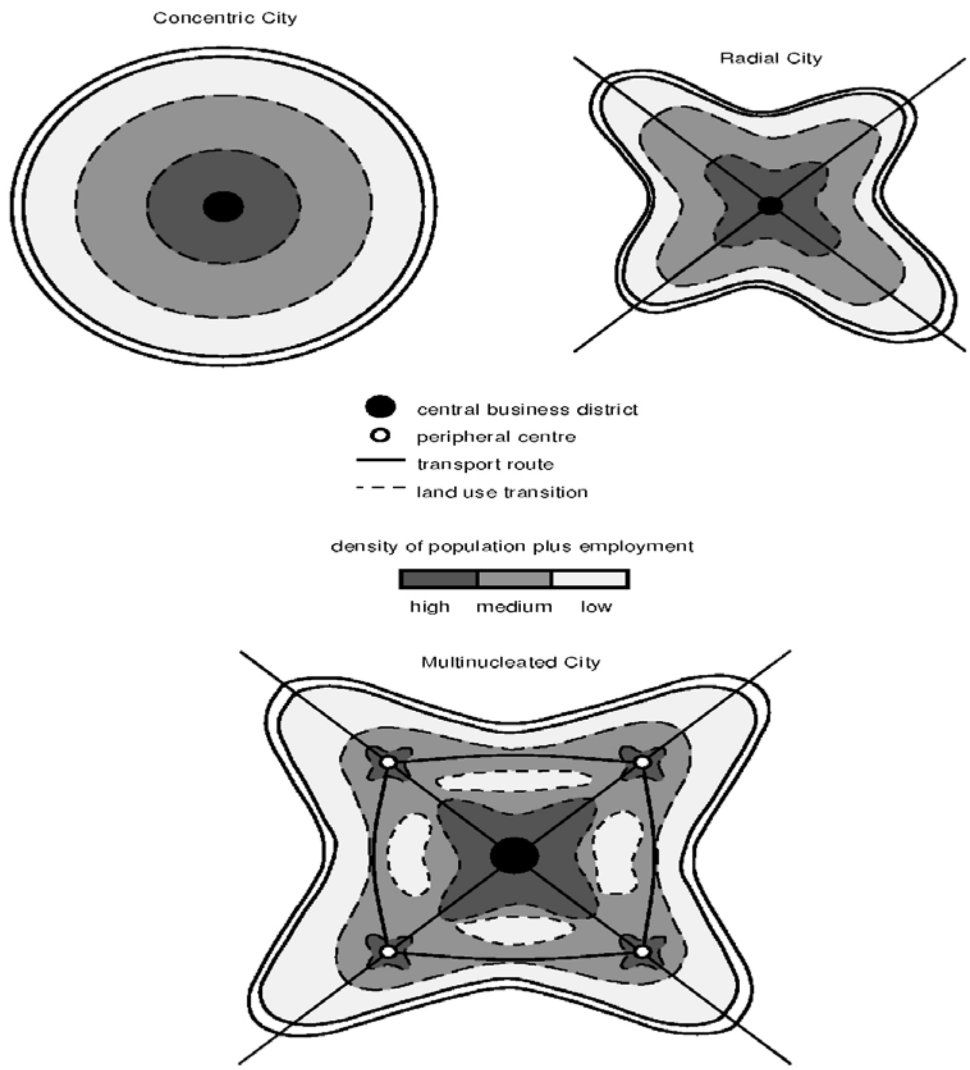


Figure 2.21 Three archetypal urban forms
Source: Anderson et al. (1996)

However, urban form affects energy consumption and CO_2 emissions via two main ways. Firstly, it affects travel behaviour, such as trip distance and modes choice, and thus the transport energy consumption. Secondly, it controls energy use in buildings such as domestic and commercial building clusters, largely through the type and the size of buildings that are developed, and this is the building energy consumption (Newman and Kenworthy 2000).

Research on the role of urban form in energy use and environmental aspects starts since the 1970s, with Owens (1986) combine the theory and practices. Urban form is heavily affected by land-use and transport. For the land use, the higher density of residence and employment has been widely accepted as lower energy consumption in cities, especially promoted the concept of the compact city represented by high density and mixed-use in many European countries (Mindali et al. 2004). High densities provide public investment maximisation and allow the more efficient use of resources. Increased the residential density combining with mixed land-use, can reduce auto ownership levels and commuting distances (Cervero 1996). Increased employment concentration in CBD and inner suburbs contribute to higher transit (Schimek 1996). Low densities, on the other hand, increase per capita cost of land, infrastructure and services, and thus reduce the degree of social interaction. Moreover, residents in these areas are forced to travel long distances to reach nodes such as work, home, education and entertainment site. However, high densities mean a greater level of access for business, more productivity and less energy and time consumption (Acioly and Davidson 1996).

(1) <u>Urban form and building energy consumption</u>

The effect of urban form on building energy consumption is a new area of exploration. The impact on building energy consumption and urban form is somewhat ambiguous mainly due to operational energy, embodied energy, building types, and different climatic contexts. A noticeable example is the positive relationships between building energy consumption and urban density for office buildings as increasing urban density will reduce the availability of daylight in particular (Steemers 2003). Wright (2008) describes the correlation between home energy consumption and a wide range of factors such as built form, location, appliances, occupant behaviour, and fuel affordability. Ewing and Rong (2008) assume urban form can affect residential energy use in three different ways as illustrated in Fig. 2.22. Firstly, it directly influences residential energy consumption through electricity transmission and distribution losses; secondly, it indirectly influences the energy consumption by the type and size of house stocks, as well as by the local temperature through the formation of urban heat islands.

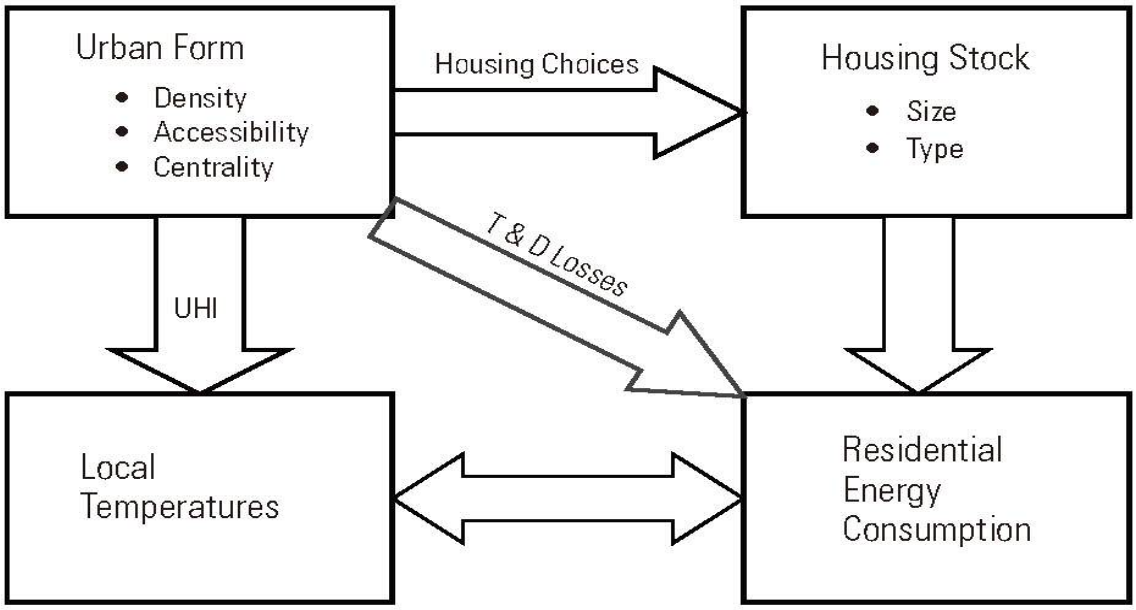


Figure 2.22 The relationship between urban form and residential energy consumption
Source: Ewing and Rong (2008)

(2) Urban form and transport energy consumption

When it comes to the correlation between urban energy consumption and the transport sector, many pieces of evidence have shown a strong negative relationship between urban density and transport energy consumption (Williams et al. 2000; Newman and Kenworthy 1989; Frank 2000; Cervero 1996; Frank and Pivo 1994). Newman has researched and written many publications about the relationship between transport energy consumption and urban density of worldwide cities. Figure 2.23 shows how increasing urban density results in less annual transport energy consumption (Newman and Kenworthy 1989).

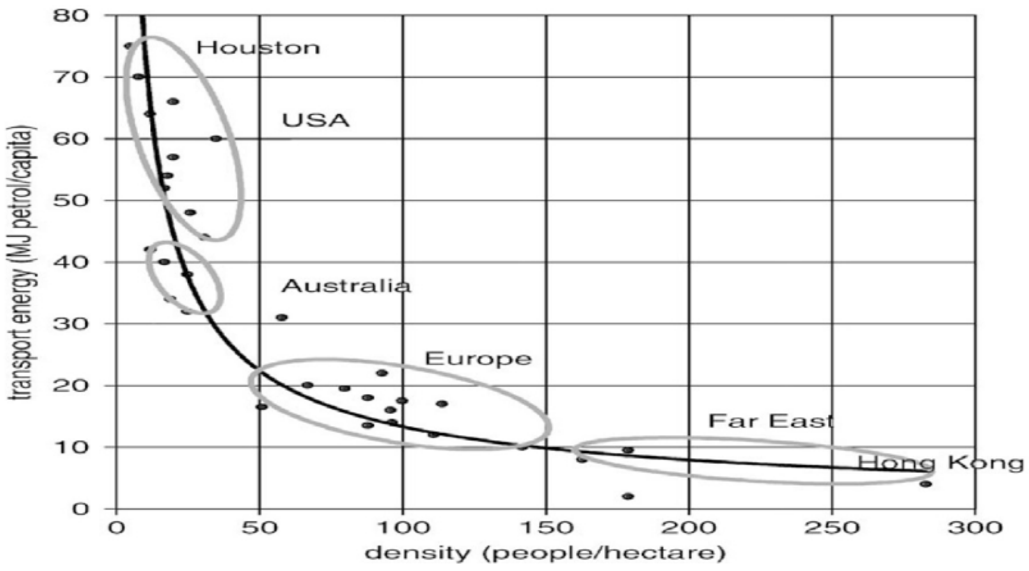


Figure 2.23 Transport energy vs. urban density
Source: Newman and Kenworthy (1989)

The results are similar when comparing per capita driven miles and energy use for high-intensity and high-income (jobs and housing density) cities from around the world (Newman & Kenworthy 2006). Their research indicates U.S. cities have the lower density and a higher per capita energy use than Canada, Australia, and Europe. This implies that decreasing density will increase transport energy consumption. Compact cities appear as the most efficient of all urban forms, with 43% less fuel consumption than other forms of urban development (Magalhaes and Durán-Ortiz 2009); hence there are the lowest carbon dioxide emissions due to more use of public transport and reduced use of privately owned vehicles. A better understanding of the transport energy consumption can be achieved by analysing the urban spatial structure, or can alternatively analyse the following elements: the urban form and the human interaction in the city centre, etc. (Bourne 1987). Brundell-Freij and Ericsson (2005) verify the relationship among urban form, modes choice and driving patterns. Giuliano and Narayan (2003) find that differences in daily trips and vehicles miles travelled are explained by differences in both of the urban form and household income. Findings show that the effect of income on daily travel is similar to the US and the UK, but the effect of density is more profound in the US. Magalhaes and Durán-Ortiz (2009) compare the carbon footprints of fuel consumption and light vehicles in Curitiba and Brasilia. The results show that Curitiba has significantly low annual average carbon dioxide emissions from light vehicles than Brasilia, although Curitiba has motorisation level that is 21.3% higher than Brasilia. However, some argue (Altshuler 1979; Gordon and Richardson 1997) that an increase in urban density does not necessarily reduce transport energy consumption. This is because vehicle ownership levels and car dependency are influenced by many variables apart from urban forms, but family income, gas price and the availability of public transport. Furthermore, Mindali et al. (2004), using the data from Newman and Kenworthy, conclude that there is no direct relationship between energy consumption and the total urban density.

2.6.3 Urban design

Research on the transport, urban design and planning have examined the correlation between physical environment variables and individuals' walking and cycling for transport. Consolidating urban places and improving the design is seen to be beneficial not only from an environmental perspective but also as a means of improving the 'livability' of urban areas, as well as providing the impetus for economic regeneration.

Urban design does not belong to one discipline and overlaps with architecture, urban planning, and landscape planning, etc. Hence, urban design theorists and practitioners still have no agreement on the definition of what urban design is. In a broader sense, urban design deals with issues of urban form and the development of urban units and their components. Saelens et al. (2003) describe that urban design is a term that makes decisions about how natural and built elements in a particular space will relate to one another, and urban designers consider how people will perceive and interact with the human-made environment. Madanipour (1997) defines the urban design as concerned with the quality of the public realm. Other theorists regard it as movements in cities (Butina-Watson and Bentley 2007). Bentley (1985) have developed seven indicators (permeability, legibility, etc.) that need to be included in urban design in the book "responsive environments —a manual for designers". These indicators to help achieve sustainable urban design relating to the environments.

Transport energy use can also be reduced by urban design mainly through minimising car use in cities. The original "3Ds" are density, diversity, and design (Cervero and Kockelman 1997), followed later by "destination accessibility" and "distance to transit". The features of these "5Ds" can be interpreted as follows:

> *Density— higher population, jobs and dwelling units per unit area;*
>
> *Diversity — a greater mix of land uses including residential, employment, and retail/services in proximity to each other;*
>
> *Design — smaller block size or larger number of intersections per square mile, more sidewalk coverage, smaller street width, more pedestrian crossings, and more street trees;*
>
> *Destination accessibility — more jobs or other attractions reachable within a reasonable travel time; tends to be highest in urban cores;*
>
> *Distance to transit — shorter distance from home or work to the nearest rail station or bus stop (Ewing and Cervero 2010, P. 267)*

Newman reviews the urban design that can reduce car dependence based on local public transport nodes, such as urban rail nodes (Newman et al. 2006). Frank (2000) has long understood that the neighbourhood design and the way of land developed and used may affect transport mode choices. Ewing and Cervero (2010) propose the concept of design focusing on street network characteristics within an area, which should be highly connected with the urban grid and applied meta-analytical methods that have also been used in the urban design field (Bartholomew and Ewing 2008; Cervero 2002).

In conclusion, urban design affects both building energy consumption and transport carbon dioxide emissions. The suitable urban design is, in part, about the balance. The balance between the use of public transport and individual cars, between the building energy consumption and transport carbon dioxide emissions, and between nature and the built environment.

2.6.4 Accessibility

Accessibility, a concept used in some scientific fields such as transport planning, urban planning and geography. Good accessibility is crucial to achieving low carbon transport, as it may reduce the length of automobile journeys or change the mode choices, thus reducing carbon dioxide emissions and transport energy consumption.

Accessibility is defined in several different ways. These include definitions of the potential of opportunities for interaction (Hansen 1959). Handy (1993) proposes the "local accessibility" and the "regional accessibility", and he believes that accessibility consists of a transport element and a spatial component. The former (local accessibility) reflects the ease of travel between points and the quality of service provided by the transport system and is measured by travel distance, time, and cost. The latter (regional accessibility) expresses the distribution of activities, such as residences, employment, recreation, offices. Also, he insists that an increase in both local and regional accessibility can lead much shorter shopping distance, but no reduction in shopping trip frequency. Geurs and van Wee (2004) use four components: land-use, transport, temporal, and individual, to describe accessibility shown in Fig. 2.24.

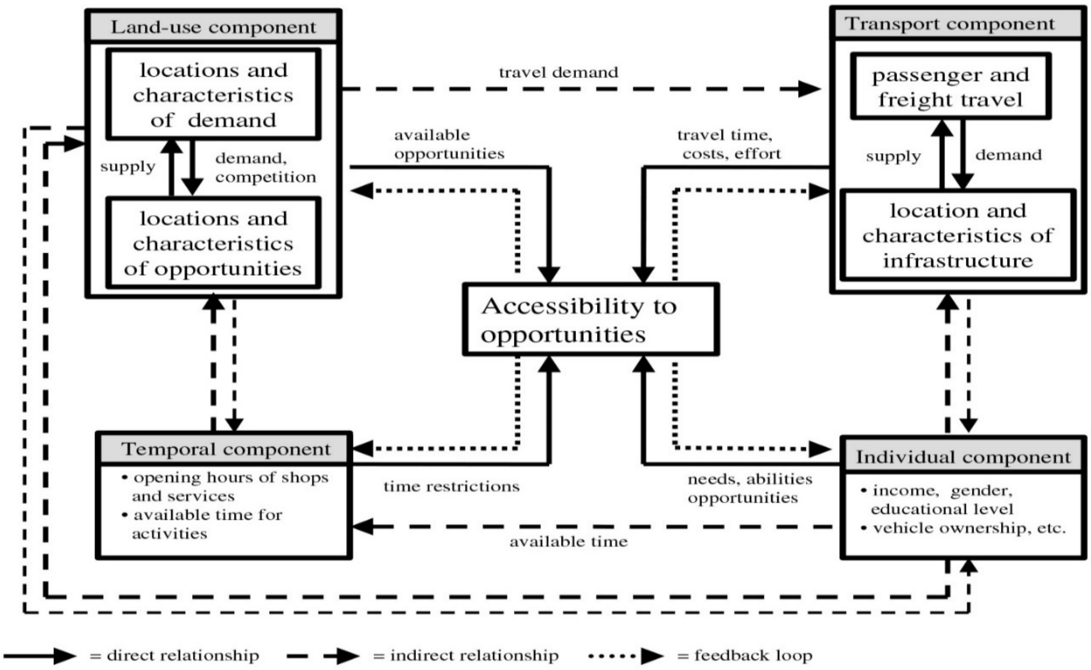


Figure 2.24 Relationships between components of accessibility
Source: Geurs and van Wee (2004)

Accessibility depends on the transport available to individuals, the temporal and spatial distribution of activities, and the social and economic roles of individuals that determine when, where, and for how long they must pursue various activities. However, when compared these different definitions of accessibility, it appears that most of the information is concerned with spatial data such as the location of nodes, the length of links, and data on transport costs measured by travel time and fares.

Accessibility measures are also concerned. Several indicators are used to measure the accessibility: travel time, congestion level, and operating speed on the road network, which is described in infrastructure-based accessibility measures to analyse the service level (Neuburger 1971; Williams 1976), and is typically used in transport policies and planning. The advantages of this infrastructure-based measures are readily available, and the results are easy to understand for policymakers. However, this measure does not satisfy most of the theoretical criteria as it ignores potential land-use impacts on transport strategies, such as the impact of improved travelling speed on urban sprawl. Furthermore, it does not correctly measure the impacts on land-use policies, which affects the spatial distribution of travel activities.

Another common type of accessibility measures—location-based measures are also used in accessibility measurement studies (Bruinsma and Rietveld 1998; Gutiérrez and Urbano 1996). The distance measures are the simplest type of location-based accessibility measures. The advantage of this simplest measurement is easy to interpret for policy-makers, as there are no assumptions on people's conception of transport, land-use and their interactions. Other types of accessibility measures, e.g. Person-based accessibility and utility-based accessibility (Koenig 1980; Miller 1999) are also studied. The former is very useful for social evaluations of land-use and transport changes (Miller 1999; Waddell 2001). The latter interprets the outcome of a set of transport choices and can be used to model travel behaviour and the benefits of different users of a transport system.

Accessibility is viewed as indicators of the impacts on land use and transport development in the function of urban areas. It means that accessibility is integrated with the role of the land-use and transport systems, which will give individuals opportunities to participate in activities in different locations. Focusing on road transport sector, the accessibility is defined as the degree of easiness from the origin to destination. The focus is given on the distance to the public transit, which is measured by the shortest distance from the residences or workplaces to the nearest bus stops or the underground stations. Alternatively, the focus is also on the transit route density: the number of stations per unit area, which can illustrate individuals to cover the distance between origin and destination using the specific transport mode, measured by travel time, travel costs, and travel self-evaluation (e.g. reliability, the level of comfort, safety risk). Figure 2.25 shows the relevant factors influencing the accessibility.

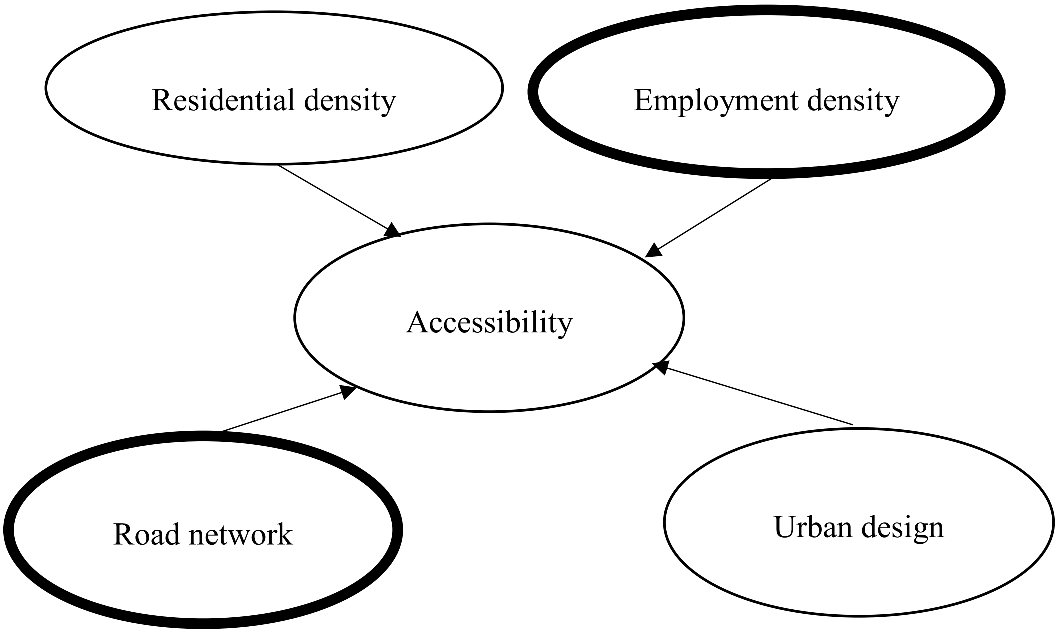


Figure 2.25 Factors affecting accessibility

Source: Adapted from Arndt et al. (2014)

2.6.5 Renewable energy applications

The term "renewable energy" comes from a broad range of resources, which can be self-renewing energy sources such as sunlight, the wind, and biomass (Bull 2001). Renewable energy can be defined in various ways that sometimes include different technologies. The general definition of a renewable energy source is one that derives energy from a non-depleting resource. The major renewable energy systems include photovoltaic (PVs), solar thermal (electric and thermal), the wind, biomass (plants and trees), hydroelectric, ocean, and geothermal (Turner 1999). At the large scale, renewable energy sources mainly originate from solar power such as solar and the wind. Compared with fossil fuels that will eventually deplete, renewable energy will never. Application of renewable energy is a modern approach to energy conservation in buildings, which can be developed about solar energy, i.e. solar thermal in the form of active and passive systems, daylighting, natural cooling, and photovoltaics (Chwieduk

2003). Renewable enegy application and promotion mainly from the perspective of the policies and technologies, and the following part will present.

Policy and typical projects

The utilisation of renewable energy sources helps to reduce the environmental impacts of air pollution. The central government has significantly boosted the development of renewable energy applications. China's 12^{th} Five Year Plan (2011-2015) states: "the production capacity of solar energy, wind energy, and geothermal energy should increase." Moreover, it implemented the 'renewable energy law' in 2005 and effected on 1st January 2006 which encourages the development of various types of renewable energy sources (State Council 2006). This law recognises that the renewable energy plays a pivotal role in the sustainable development in China. It also clarifies the responsibilities of governments, private developers and ends users during the whole development process (Zhao et al. 2011).

A common renewable energy practice is launched in Dezhou city in Shandong province, and the local government wants to make the city become the "solar city". As a result, the city widely applied solar energy technology, which includes the installation of solar water heaters on the roofs and facades of residential buildings; the use of solar PV to street lights in the main streets, and the integration of solar PV with buildings for the daily supply of electricity (Goess et al. 2015). Other examples from the Jiangsu provincial government that also issued the notices on the solar photovoltaic industry to encourage the solar photovoltaic power. It specified that the government would devote to developing the solar power industry by releasing supporting policies, establishing relevant standards, and providing fiscal incentives. A goal is set up to achieve 400 MW installed capacity of solar photovoltaic power connecting to the grid by 2012 province-wide (Zhao et al. 2011).

Renewable energy technology for buildings

Each technology has its characteristics that determine its use and suitability; it is, therefore, important to consider how that technology will work for a particular building. These include (Day et al. 2013):

1) Building type, function, and form;
2) The buildings' energy demand;
3) Building occupancy and their behaviours;
4) Local site and climatic conditions;
5) Regulation, planning, and other requirements;
6) Shading from neighbouring buildings, structures, and trees, etc.

Four most frequently major renewable energy technologies utilised on buildings are listed in the following parts (Chwieduk 2003; Day et al. 2013)

- Bioclimatic building design

Using passive solar and making use of the building itself, either to gain as much solar energy as possible or to protect the building from the sun, depending on the season and climatic conditions, are connected with the proper design of building surroundings, such as trees and application of daylighting.

- Shading

Solar shading affects energy demand in buildings through solar gains caused by trees, buildings, and other structures. It also can modify thermal losses through windows. Shading devices influence daylighting levels in a room. Shading is thus closely connected with energy consumption in buildings for heating, cooling demand, and lighting;

- Solar PVs

Solar PVs consist of PV cells that convert solar energy directly into electricity via the photovoltaic effects. Unfortunately, the voltage created by a single PV cell is tiny.

- Solar thermal

There is a high potential for solar thermal application. It is a good choice to heat domestic hot water in the residential buildings because they are easy to install. However, the main utilisation of solar thermal is restricted due to the high cost and depends on the climates. Therefore, financial incentives have been made available for the installation of this application and are only applicable to countries with hot climates.

2.7 Modelling building energy consumption and road transport carbon dioxide emissions

An understanding of the urban building energy consumption is essential for low carbon development in existing buildings that are energy inefficient. Furthermore, the modelling approach are used to formulate policy decisions regarding on the building stock, both the old and new. By quantifying the energy consumption, it can be made to support energy supply, retrofit, and technology incentives.

This section (2.7.1) reviews the approach to calculating the building energy consumption. The next section (2.7.2) examines methods to estimate transport-related carbon dioxide emissions on the road in urban areas. Both approaches are vital for studying the urban energy and associated carbon dioxide emissions reduction.

2.7.1 Buildings energy consumption modelling

The attention to saving building energy consumption has always been focused on the single building level. However, concerning energy use and carbon emission reduction, it is crucial to widen its scopes to the community and urban level because there are huge potentials for energy-saving and carbon dioxide emissions reduction for the large-scale building stocks (Fracastoro and Serraino 2011). Moreover, energy consumption in the building stocks is highly diverse, being influenced by a range of factors such as building types, equipment systems, and occupant behaviours. Therefore, an approach to predicting urban building energy consumption can be an extremely complicated process because of the extensive data input, and because of the great urban building energy modelling, thermal modelling, and validation.

Governments usually publish a simple estimation of the total building energy consumption at the urban scale through statistics approach, which compiles gross energy consumption submitted by energy providers (Swan and Ugursal 2009). For example, Chen et al. (2008) propose the framework of the national statistics for building energy consumption shown in Fig. 2.26. However, this method would be inaccurate as some unreported energy consumption may be ignored.

Fortunately, the rapid development of computational technologies, such as Geographic Information Systems (GIS), some professional software such as HTB2 developed by Cardiff University, and Energyplus created by the US Department of Energy could make the calculation and decision-making more accurate on the buildings at the large scales.

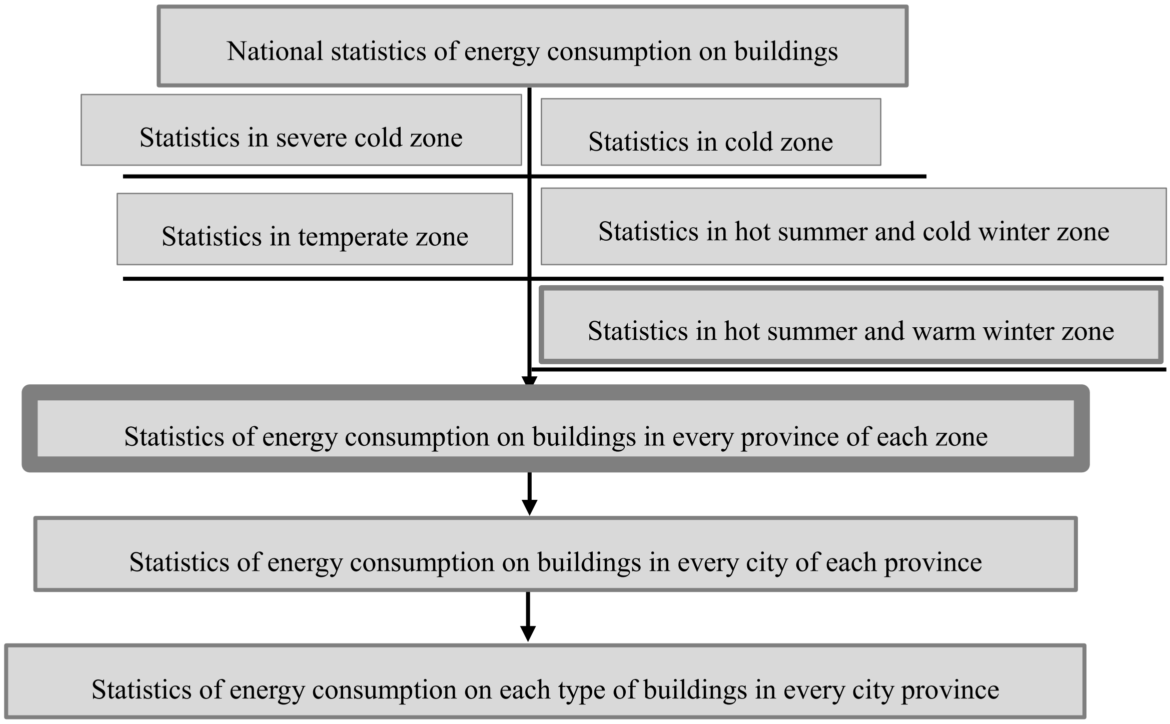


Figure 2.26 National statistics framework for urban energy consumption
Source: Chen et al. (2008)

Some computer models have been developed that be valuable to planners seeking to make rational decisions on energy management in the urban environment over the past decade (Caputo et al. 2013; Shimoda et al. 2004; Dall'O' et al. 2012). Table 2.9 illustrates the energy consumption and carbon dioxide emissions estimate from the models at different scales: individual and urban scales.

Table 2.9 Different carbon dioxide emissions calculators at different scales
Source: Carney and Shackley (2009)

Model	Scale/Application	Other References
National air emissions inventory	UK	All six 'Kyoto' greenhouse gases
DREAM	City/urban region	High-resolution data required
EEP	City/urban region	High-resolution data required

Greenhouse gas protocol	Company	Detailed company data needed
Leicester model	City	
Various	Individual	Lifestyle emission calculations
REAP	Sub-national	End-user including embodied energy

Techniques used to model energy consumption are classified in two main categories: "top-down" and "bottom-up" approach (Swan and Ugursal 2009). The top-down method estimates the total sector energy consumption and allocates the energy consumption to the entire floor area of individual buildings by some variable such as the size of the house. In contrast, the bottom-up method calculates the energy consumption of individual or groups of buildings using small and simple models with similar features and then extrapolate these results to represent the region or nation based on the weight of the modelled sample (ibid.). The available prediction approaches of the "top-down" and "bottom-up" are clustered as in Fig. 2.27.

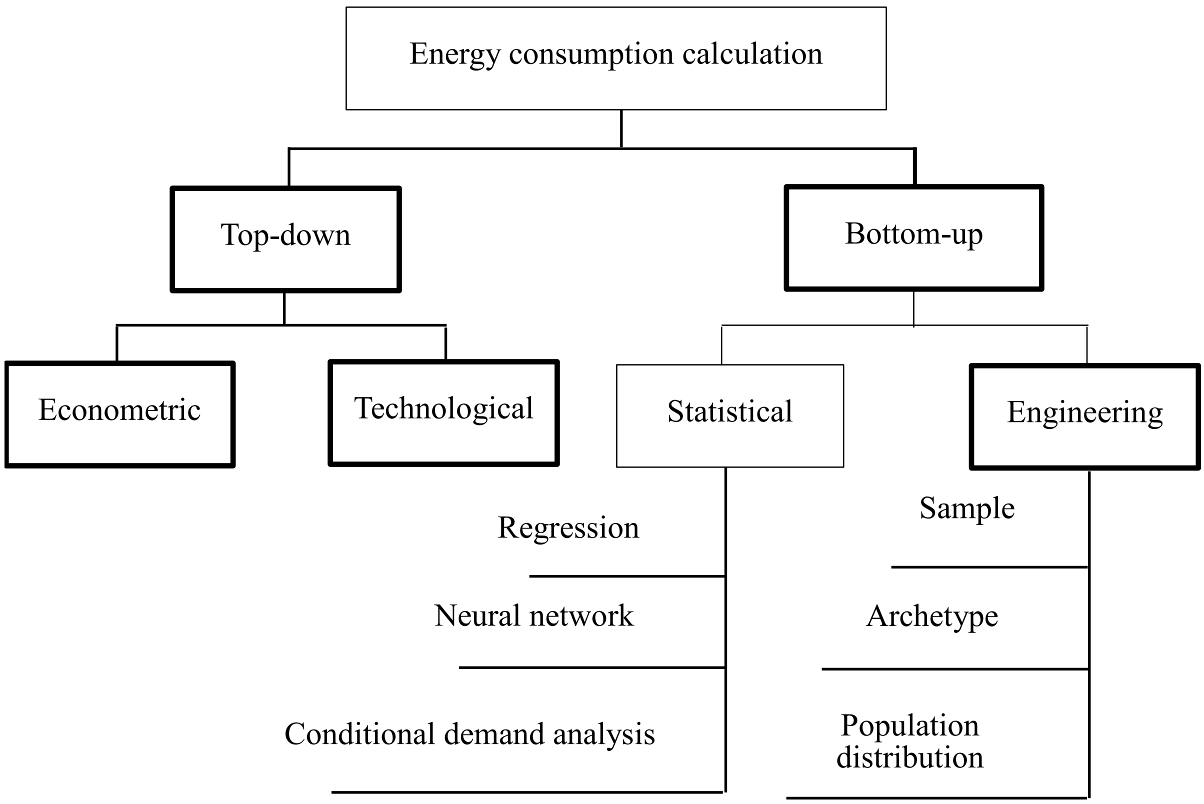


Figure 2.27 Modelling techniques for estimating the urban scale energy consumption
Source: Swan and Ugursal (2009)

Jones et al. (2001) develop an energy and environment prediction model (EEP) based on GIS techniques to estimate the city-scale energy consumption considering the difference of building types. The model adopts the standard assessment procedure (SAP) to simulate building energy demand based on building fabric, ventilation, space heating, and cooling. Moreover, this model considers the environmental and surrounding influence on building energy performance.

Yamaguchi et al. (2007) quantify the total end-use energy consumption from the commercial sector in Osaka city at the municipal level using “district clustering modelling approach”. However, this method is impossible to allocate a specific amount of energy consumption to buildings, especially the energy supply from the district heating and cooling systems.

Titheridge et al. (1996) develop a city model of DREAM (Dynamic Regional Energy Analysis Model) to calculate urban energy and emissions. The city model includes the urban domestic, services, industrial and transport sectors, which can be run independently, and then using the graphical or tabular results from the models to analyse the city's energy demand and supply. It also predicts carbon dioxide emissions.

Huang and Brodrick (2000) use a bottom-up engineering approach to estimate building energy use of the residential and commercial buildings, and then utilise top-down statistical approaches to scaling their results up to the national level.

Brownsword et al. (2005) have developed urban energy consumption model using energy supply data and postcode information. The model simulates spatial variations in energy demand and the effect of energy management measures and associated reductions in CO_2 emissions through a linear programming optimisation module.

The common benefit of these different methods is to provide the most complete and comprehensive prediction of energy consumption and thermal performance in buildings. However, one of the problems from all these modelling approaches is heavily depending on the details of building and environmental parameters as the input data. These parameters are unavailable to many organisations and personal use. For example, the information of the occupants' activities in the large office buildings is very tough to obtain. As a result, the lack of accurate data can lead to reducing the probability of precise simulation. Secondly, some of these models only focus on residential sector and are not applicable to commercial buildings or transport buildings, and others simulate energy demand on an annual basis but do not reflect the important variation in both energy supply and demand. Finally, many models are too tough for ordinary users to operate, understand other than developers themselves, making it difficult to perform and cost inefficient due to the need for very professional knowledge.

2.7.2 Road transport carbon dioxide emissions modelling

Road vehicles are regarded as the significant sources of transport-related CO_2 emissions (Metz 2001). It has been estimated that carbon dioxide emissions from road traffic worldwide will increase by 92% from 1990 to 2020 (Gorham 2002). 20% of the world's energy consumption is attributed to road traffic: among this, 13% is for passenger transport (Schafer and Victor 1999). Meanwhile, the number of the private cars would increase dramatically. As a result, road transport-related CO_2 emissions have received particular attention due to the constant rise in car numbers. Although some methods are used to reduce carbon dioxide emissions on the transport, i.e. better transport planning, and better transport demand management, the estimation of traffic flow has been used mostly to make decisions for policy-makers to reduce carbon dioxide emissions (Carmichael et al. 2008; Mensink and Cosemans 2008). What is more, the prediction transport-related CO_2 by modelling can be a powerful method for air quality control.

Much of the road traffic study focuses on models that can simulate real-time traffic flow and conditions (Nejadkoorki et al. 2008). These models are used to monitor and solve road traffic issues, such as predicting traffic flow demands. The output of such traffic models is usually expressed by vehicle speeds and traffic volume at peak hours for a given length of the road. Studies have shown that there have been two main approaches adopted to predicting road traffic carbon dioxide emissions: macro-scale approach and micro-scale approach (Namdeo et al. 2002; Reckien et al. 2007; Tuia et al. 2007). For the former method, carbon dioxide emissions are predicted to take into account the information about average vehicle speed, and average distance travelled for a large area in an extended period (usually a year). The latter method can be applied to predict carbon dioxide emissions in a shorter period even an hour, using detailed traffic data such as speed, vehicle type, and its distance travelled (Nejadkoorki et al. 2008). It has been argued that the utilisation of the micro-scale approach is much better and accurate than the macro-scale approach (Namdeo et al. 2002) as traffic densities and speeds can change significantly over a short time and a short distance.

Nejadkoorki et al. (2008) use road traffic model (SATURN) coupled with programming software (MATLAB) to predict road transport-related CO_2 emissions for an urban area. ArcGIS is used in the approach to the spatial display of the results. The modelling approach is shown in Fig. 2.28.

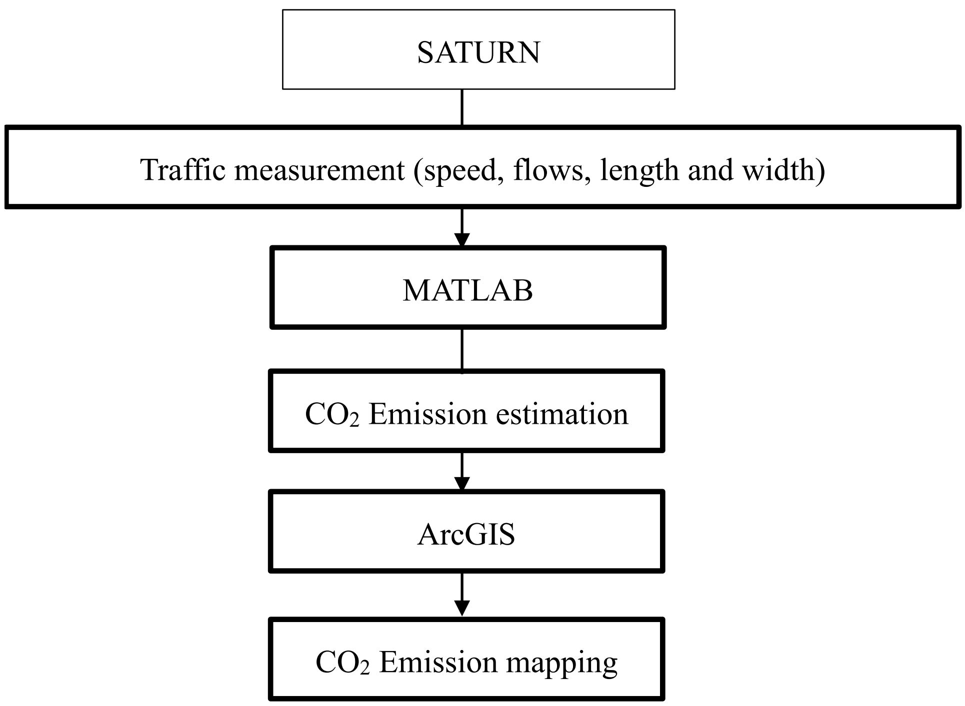


Figure 2.28 The modelling approach for road transport
Source: Nejadkoorki et al. (2008)

The input data in this modelling approach include the information about a trip matrix, and a road traffic network (Nejadkoorki et al. 2008). The study areas are categorised into different zones called traffic analysis zones (TAZs) according to the similar land use function. Traffic demand data are represented in Passenger Car Units (PCUs) and are illustrated by the number of journeys that need to be made between each TAZs for each time unit. The traffic demands are coded by the matrix, which includes rows and columns. The traffic network is based on the information for junctions and individual roads (free flow speed and road length). Both the matrix and traffic network are input into a road choice model (ibid.). The analysis of the results is possible after the assignment of traffic demand, and the program is displayed in a variety of information such as one road specific traffic volume.

Namdeo et al. (2002) using the Traffic Emission Modelling and Mapping Suite to estimate carbon dioxide emissions (CO_2) on road transport. The calculation considers road link length, vehicle flow and speed, and fuel type and their emission factors. Mitchell et al. (2011) use land use and transport interaction models (LUTI) that can provide the potential to assess regional energy demand in a sensitive manner addressing mobility patterns and transport energy consumption.

The modelling approach is a highly useful tool for predicting traffic conditions in future scenarios. These methods are especially important in the case of traffic-generated emissions since there might be an opportunity to reduce total emissions by urban restructuring, developing road networks, and changing traffic demands. Transport planners and environmentalist can simulate how much road traffic related carbon dioxide emissions could be produced using different plans. However, one weakness of these modelling methods is that road network usually only contains major roads. As a result, it is only suitable for calculating traffic flow on the main roads. Furthermore, all these models are complex and challenging to understand rather than by these developers themselves. Finally, all these methods need extensive input data, which is a challenge because of the uneasy collection such as the travelled distance, and the percentage of each modal split.

2.8 Summary

Literature review in this section consists of four parts relating to theories and practices in green urban development, the situation of energy consumption on buildings and road transport, relevant factors affecting building energy consumption and transport-related carbon dioxide emissions, and finally modelling development in the building stocks and transport sector from different scales.

Green urban development will be the focus of the existing built environment

Various concepts for green urban development in China have been proposed, from the original green city to the final low carbon eco-city, and this shows that the government realises its importance of the sustainable urban development, not only focus on the GDP development, but also on the environmental issues. Different practices and projects relating to green urban development from China and the worldwide are also presented. Some strategies are adopted to promote low carbon city development. These strategies focus on the idea of reducing car dependence on short trips, and of promoting public transport for long trips such as public transport orientation, TOD (transit-oriented development), and sustainable urban form development measured by mixed land use on transport sector and passive design and renewable energy applications on building sector.

The situation of energy consumption and carbon dioxide emissions on buildings and transport sector

The condition of building energy consumption and transport-related carbon dioxide emissions in China are reviewed and analysed. For the building energy consumption, firstly, there is an upward trend because of the rising construction of annual floor area in cities due to the rapid urbanisation rate. Secondly, different building categories significantly vary in the level of energy consumption. Energy consumption on large-scale commercial buildings is higher than other building types, even more than ten times. Thirdly, space heating in the north areas occupied most of the total urban building energy consumption due to the climatic conditions and large floor area of residential buildings in cities.

For the transport-related carbon dioxide emissions, there is a rising trend in the number of private vehicles and more transport demand between cities than before. This dramatic increase has resulted in the rapid growth of transport-related carbon dioxide emissions. Two approaches are presented to reduce the transport-related carbon dioxide emissions from the technology improvement and the planning aspect (urban planning and transport planning). Firstly, it can improve the fuel efficiency of automobiles and develop the alternative energy such as renewable energy applications. Secondly, the core idea is to avoid unnecessary travel and reduce trip distances by appropriate planning.

Influenced factors on building clusters and transport-related carbon dioxide emissions

Although many factors affect energy consumption and carbon dioxide emissions in buildings and transport sector, this part primarily reviews selected factors including national policies, urban form and design, accessibility, and renewable energy applications. National policies about the standards and regulations focus the energy efficiency on residential and public buildings, and thus low energy demand from buildings. The problems are that these standards are very obsolete, narrow scope and lack a strong framework to strengthen energy efficiency, especially in the construction process. Moreover, the unwillingness of local governments to carry out these standards in practice is the biggest barrier for low carbon city development. For the transport sector, it focuses on the reduction of road transport-related carbon dioxide emissions, such as the policy of optimising the transport structure, and promoting public transit. All these policies are to direct energy efficiency in buildings and reduce CO_2 emissions in transport. **Secondly,** for the urban form and urban energy consumption, it analyses both the relationship of urban form between building energy consumption and transport-related carbon dioxide emissions. The results indicate that urban form and building energy consumption is somewhat ambiguous mainly due to operational energy, embodied energy, buildings types, and different climatic contexts. For the urban form and transport-related carbon dioxide emissions, numerous studies have agreed with the results that compact urban form can contribute to sustainable transport development due to the reducing trip distances and avoiding unnecessary travel. Thirdly, for the urban design, it reviews its definition and several indicators that contribute to low-carbon city development and then analyses the transport-related carbon dioxide emissions reduction with urban design through strategies by "3Ds" (density, diversity, and design). Moreover, for the aspect of accessibility, the review focuses on the concepts, measurement, and factors affecting accessibility. Finally, this research reviews renewable energy applications relating to policies issued and joint projects applied in China, and then applications of renewable energy on buildings, such as solar PVs and shading, are presented.

Modelling development on building energy and transport-related CO_2

By reviewing the modelling of building energy consumption and transport-related carbon dioxide emissions, this study understands that methods to investigate carbon dioxide emissions from building sector and road transport are bottom-up and top-down. The top-down method adopts the total sector of energy consumption and allocates the energy consumption to the entire individual building by some variables such as climatic conditions and number of occupants, and this method is used to define the long-term modifications of energy requirements trends. In contrast, the bottom-up method calculates the energy consumption of individual or building clusters with similar features and then extrapolates these results to identify the regional or national level based on the weight of the modelled samples. The potential of such models is based on the physical features and boundary conditions of buildings rather than statistical and mathematical relations. For this reason, these methods can provide the most complete and comprehensive prediction of energy consumption and thermal performance of buildings. However, one problem of all these modelling approaches heavily depends on data input from buildings. Secondly, some of these models are not applicable to other building categories; the annual-based energy demand cannot reflect the important variation in both energy supply and demand. Finally, many models are too tough for ordinary users to operate, understand other than developers themselves.

For the prediction of transport-related carbon dioxide emissions, there are mainly two approaches classified by the macro-scale approach and micro-scale approach. For the former method, the calculation of carbon dioxide emissions considers the data from the aspect of annually travelled distance and modal splits. The latter one can be applied to predict transport-related carbon dioxide emissions for individual roads in a shorter period even an hour, using specific traffic data such as speed, vehicle type, and its travelled distance. It has been argued that the utilisation of the micro-scale approach is much better and accurate as traffic densities and speeds can vary shortly over a period and distance, but this method is more complex to obtain the data required. However, the weaknesses of these methods are also identified. These weaknesses revolve in the challenge of data input, the complex model to understand, and the limitation for CO_2 computation.

Chapter 3 Research Methods and Framework

3.1 Introduction

Chapter Three investigates available methods and appropriate models to understand, analyse, and predict operational energy consumption and its associated carbon dioxide emissions from buildings and transport due to the mobilities of users from buildings. This study adopts methods that combine both quantitative and qualitative research. Quantitative analysis is carried out by building energy models, activities-based transport demand models, parametric analysis and multinomial logistic regression. The qualitative research includes methods of the literature analysis, on-site surveys and questionnaires. The methodologies and framework are presented in Fig. 3.1 as follows：

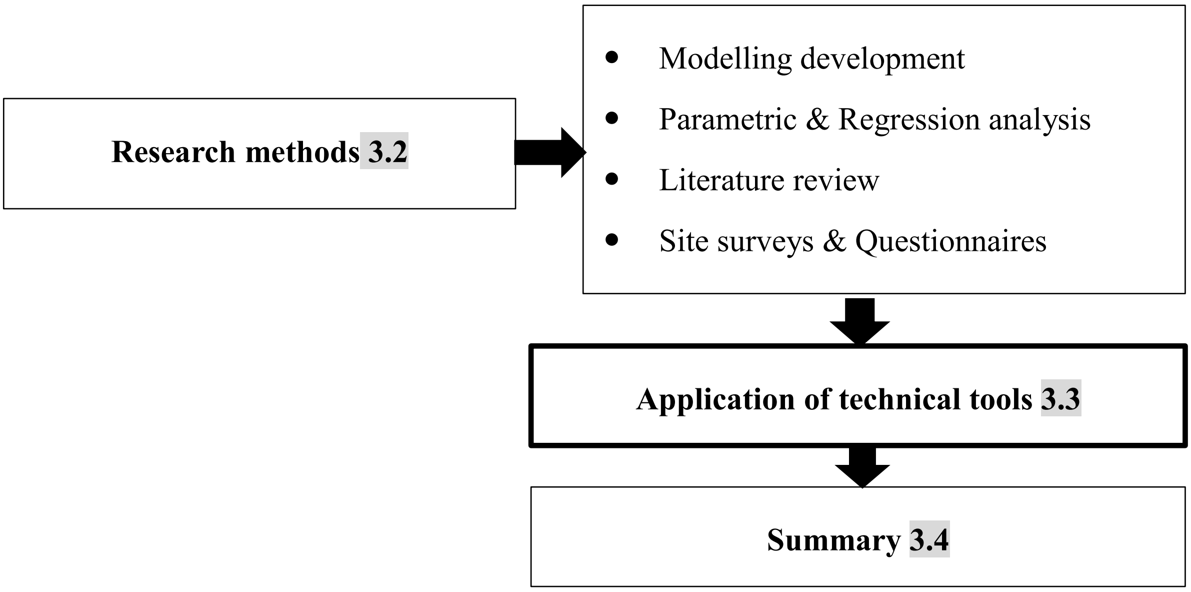


Figure 3.1 Flow chart of this chapter

3.2 Research methods

3.2.1 Building energy model

A better understanding of the energy consumption and associated carbon dioxide emissions from buildings in cities are essential for low carbon city development. In general, it is possible to distinguish two different methods to investigate energy consumption and associated carbon dioxide emissions from the buildings, namely top-down and bottom-up approaches (Ho 2010; Swan and Ugursal 2009; Kavgic et al. 2010).

The development and application of the bottom-up approach for the modelling building began in the mid-1990s (Foliente and Seo 2012). Since then many studies have adopted this approach for modelling residential building clusters or mixed use of building clusters (Shorrock and Dunster 1997; Swan and Ugursal 2009; Snäkin 2000; Huang and Brodrick 2000). Further developments and detailed comparison and analysis of the applications and limitations have been comprehensively discussed, and future research opportunities have been identified (Foliente and Seo 2012; Swan and Ugursal 2009; Kavgic et al. 2010). On the other hand, top-down models split into two groups: econometric and technological. Econometric models are based on the local population, income level, technology development and employment conditions. Technological models attribute the energy consumption to general characteristics of the entire building cluster such as appliance ownership trends (Swan and Ugursal 2009). Moreover, aggregated levels are adopted in this model typically for the national scope and is focused on broad econometric or technological impacts.

However, one of the limitations of the top-down approach is that the lack of details regarding on the energy consumption of individual end-users eliminates the capability of identifying key areas for improvements in the reduction of energy consumption.

Conversely, the bottom-up approach provides flexibility and the powerful capability to investigate the full impacts on a specification at higher levels of aggregation, from the community level to the national level. Then again, this approach is highly dependent on the data of availability, reliability and capability of the model used, and the modelling technique may be based on building physics, statistical models or a combination of the two (Kavgic 2010).

For the building cluster in this study, building energy modelling to calculate energy use and associated carbon dioxide emissions is implemented at the neighbourhood level. Energy performance simulation tools HTB2 (Heat Transfer in Buildings) and Plug-in VirVil (Virtual Village) is adopted to calculate carbon dioxide emissions for building clusters. Being a research tool rather than a simple design toolkit, HTB2, developed by Cardiff University, is intended to demonstrate comprehensive operation prediction of internal environmental conditions and energy demands of a building, during both the design stage and its occupancy period. It can predict the influence levels of fabric, ventilation, solar gains, shading and occupancy on the thermal performance and energy use of a building (Lewis and Alexander 1990).

3.2.2 Activities-based transport demand model

The principal equation for calculating carbon dioxide emissions is obtained from the combination of two variables: emission factors (EFs) and the data of transport activities. There are two main approaches currently used for predicting transport-related CO_2 emissions: top-down and bottom-up (Ho 2010).

A top-down approach starts estimating the total emissions by using total activities for the whole domain and average emission factors. Then, it uses several assumptions to distribute these emissions in space and time (Friedrich and Reis 2004). This approach is easy to apply because it needs little input information and time to generate results. This method is particularly appropriate to estimate the total emissions on a large scale such as a national level. One of the main limitations of this approach is the results of spatial emissions inventory are usually highly uncertain (Ho 2010).

The bottom-up approach is based on a source of oriented inquiry of all activities and emission data. It starts to evaluate the spatial and temporal resolution of the parameters used to calculate the emissions. This approach is more accurate than the top-down approach of evaluating the spatial and temporal resolution. It is appropriate on a smaller scale, such as the community level. However, one of the disadvantages of this method is that it needs a significant amount of input data for generating carbon dioxide emissions. Moreover, the time for generating carbon dioxide emissions is longer than the top-down approach.

For the travel activities due to the mobility of users from buildings in this research, the prediction of transport-related CO_2 emissions can be estimated from the bottom-up method based on the vehicle kilometres travelled (VKT). As a result, the activities-based transport demand model in equation (3-1) is proposed (Cai et al. 2012):

$$\mathbf{E} = \mathbf{e} * \mathbf{a} \qquad (\mathbf{3-1})$$

Where $\boldsymbol{E}$ is the amount of carbon dioxide emissions from travel activities; $\boldsymbol{e}$ is the emission factor, usually expressed in kg/km and primarily related to modes choice; $\boldsymbol{a}$ is the amount of travel activities which are one of the key input data to estimate transport-related carbon dioxide emissions. Travel activities are defined in equation (3-2) as (ibid.):

$$\mathbf{A} = \mathbf{n} * \mathbf{i} \qquad (\mathbf{3-2})$$

Where n is the number of the vehicle in different categories, and i is the average distance travelled by each vehicle over the time unit, in km.

3.2.3 Parametric analysis in the building sector

After the calculation of carbon dioxide emissions, the degree of how the selected factors affect the energy consumption on building clusters are explored. These factors are categorised by street orientations, the layout of building clusters, overshadowing, and the UHI effects. All these factors are explored and analysed relating to their impacts on **cooling demand, heating demand, and solar gains.**

Street orientations

Streets, as part of urban open spaces, play a significant role in creating the urban microclimates as street orientation influences the amount of solar radiation received by street surfaces as well as air flows in urban canyons. The urban streets are expressed by the ratio of height to width (H/W) and also the orientation which is defined by its long axis (Shishegar 2013). These parameters directly influence the absorption and emission of solar radiation.

In this research, the slab-built form acts as the basic form, as proposed by Martin and March (1975), to analyse different variables on the energy performance of building clusters. To compare how street orientation alteration affects the cooling demand, heating demand, and the solar gains of building clusters, we set only the orientations as the variables (δ=0; 45; 90;135), variables such as the floor area ratio, building density, storeys, height, COP, remain constant. The parameters can be set in four different orientations, from 0 degrees to 135 degrees, with 45 degrees intervals.

The layout of building clusters

The layout of building clusters in this research uses a horizontal and vertical layout. For the horizontal layout, the alteration of the ratio Wy to Wx, ΔX to Wx, △Y to Wy are examined. Other variables, such as the density, floor area ratio, building storeys, and their heights, the HAVC systems will remain the same with each case. Then, the vertical layout of building height difference is also explored. We use these indicators to measure how this alteration affects energy demand in building clusters. Detailed information about this section can be referred to Chapter 7.

Overshadowing

Overshadowing is an important and complicated issue, and there is no doubt that over-shadowing can practically reduce the energy demand of building clusters, especially the cooling demand as over-shadowing offers more shading for buildings located in urban areas, which indirectly leads to solar gain and cooling demand reduction.

This research examines the impacts of over-shadowing on cooling, heating demand, and solar gains. Three cases are analysed adopting the method of Jones et al. (2009) as the reference. Detailed information can be found in Chapter 7.

UHI effect

Temperature distribution in urban areas is highly affected by the solar radiation on the urban surfaces where it is absorbed and then transformed to sensible heat. Buildings, especially the component of vertical walls and roofs, are the solar radiation receiver.

Although many factors are related to UHI effects, variables such as population density, ambient temperature, sky view factor, anthropogenic heat, building design and materials play an important role in increasing heat intensity (Rizwan et al. 2008). As the UHI effects would be a mutual response of these variables, a comparison should consider all controllable factors and should not be limited to any other factors. This study chooses a parameter to represent the microclimate impacts on building energy demand to research the significance of UHI effects; the variable of ambient temperature increases or decreases by 1°C compared to the standard model (ambient temperature remains constant) are researched on the energy demand based on the reference of Ihara et al. (2008) who applied multiple regression analysis to analyse the relationship between the electricity consumption and ambient temperature. For a detailed process, refer to Chapter 7.

3.2.4 The regression analysis of modal splits in the transport sector

As for the regression analysis of modal splits, it analyses the travel patterns from respondents (such as travelled distance, travel time, frequency and their purposes), socio-economic characteristics, and finally self-evaluation on travelling (i.e. congestion situation, comfort level, and travel cost in travelling).

Socio-economic characteristics of respondents

Socio-economic variables were self-reported in the survey. Previous studies have found that socio-economic variables are strongly associated with travel mode choice (Stead 2001; Badoe and Miller 2000). To measure the effect of travellers' socio-economic characteristics on the probability of mode choice, **we controlled for the gender, number of household cars and household income**. Gender was measured as a nominal variable; cars were measured in numbers as a continuous, ordinal variable; monthly household income was ordinal, with four categories (0–10,000 CNY, 10,000–

15,000 CNY, 15,000–20,000 CNY, and more than 20,000 CNY). A positive relationship was expected between mode choice and household cars and income.

Travel patterns

Travel patterns cover factors **of travel time, distance, purposes and frequency**. These four factors are regressed with the modal splits to analyse the probabilities of one mode choices with another.

Self-evaluation on travelling from respondents

To examine the potential impacts of self-evaluation on mode choice due to the congestion, comfort and economical level, the respondents were asked to answer questionnaires respectively.

How would you evaluate your congestion situation while travelling?

Very smooth	Fairly Smooth	Common	Fairly Serious	Very serious
1	2	3	4	5

How would you evaluate your comfort level while travelling?

Very comfortable	Fairly comfortable	Common	Fairly uncomfortable	Very uncomfortable
1	2	3	4	5

How would you evaluate your economical level while travelling?

Very economical	Fairly economical	Common	Fairly uneconomical	Very uneconomical
1	2	3	4	5

3.2.5 Literature analysis

Literature analysis primarily includes:

(1) Review the development of high-speed railway stations and its new urban districts in China and review the theories of green urban development and its typical projects.

(2) Review energy consumption on buildings and road transport sector.

(3) Review and identify factors affecting energy consumption and associated carbon dioxide emissions from building clusters and transport sector, and

(4) Review the modelling development to quantify carbon dioxide emissions from buildings and transport activities due to the mobilities of users from buildings.

3.2.6 Site surveys and questionnaires for data collection

Site surveys and questionnaires are used for data collection from both building clusters and travel activities due to users from buildings. In this study, basic information modelling building energy is from a site survey to calculate building energy consumption and its associated carbon dioxide emissions. This information relates to physical dimensions of buildings, the construction and materials details, and operating schedules. For the transport-related carbon dioxide emissions, data of travel patterns, such as modal splits and its percentage, travelled distance, and emission factors for the computation of CO_2 emissions, are obtained by questionnaires and surveys, although it is a challenge to collect some data.

Building cluster

Data on building clusters in the study area are collected through national and local authority documents, site surveys, and maps. Energy consumption around the study area from the buildings including residential, office, commercial, and hotels or a combination of at least two of the above functions is investigated. The general survey, key survey and data analysis are used for data collection shown in Fig. 3.2. The purpose of the general survey is to collect general information such as the age of constructed buildings, operational schedule in buildings, and building floor areas and physical dimensions of buildings. The key survey is on the site, and it mainly checks and records information such as the operational schedule from face to face interview with the clients, the monthly energy consumption of electricity and natural gas from the buildings. The data analysis is to analyse the energy consumption from buildings on the investigation. The data collection includes the following parts for the building cluster:

- Population density;
- The overall energy consumption of electricity and gas from building clusters;
- The construction details, storey, physical dimensions, and ages of buildings;
- The thermal physical property of materials from buildings;
- The glass ratio;
- The indoor design conditions, and schedules;

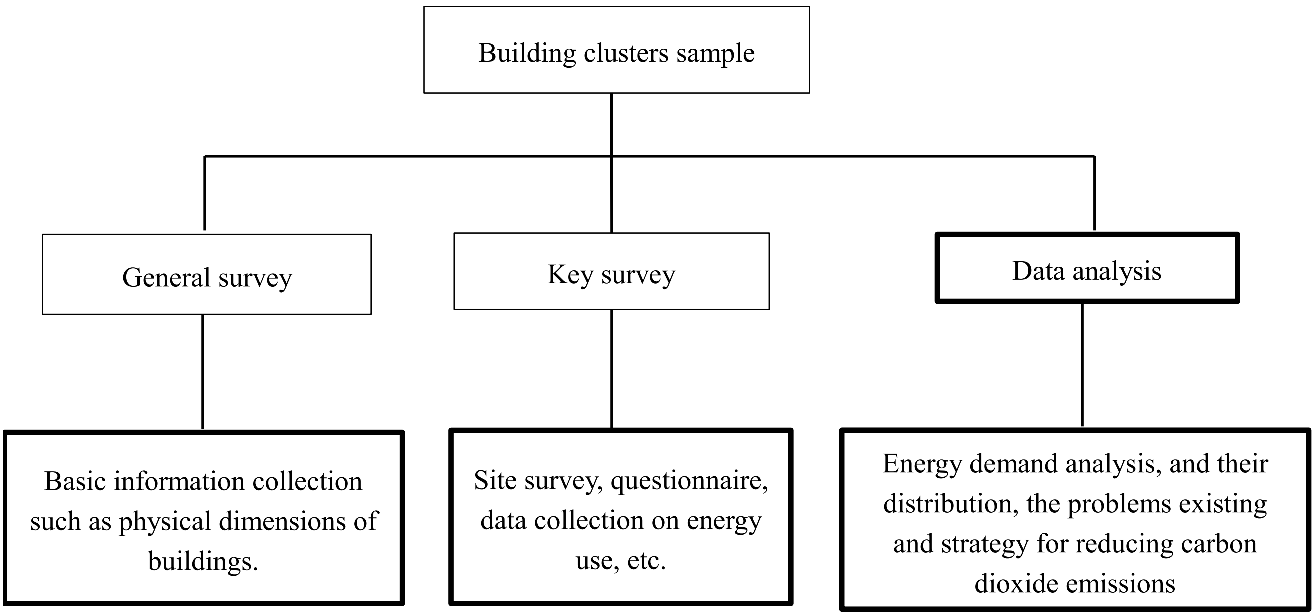


Figure 3.2 The flow chart of the on-site survey for building clusters

For the transport sector：

The carbon dioxide emissions from the transport are primarily based on the travel mode choice and travelled distance. In the survey, modal split, travelled distance, travel time, frequency and purpose are collected in the study area. However, the focus is on the travel modes and travelled distance.

1) Travel activities survey

In this study, students from the Wuhan University of Technology manually recorded travel activities by questionnaires, and they are distributed in three study areas. Travel modes are grouped into three categories based on the amount of carbon dioxide emissions features. They are non-motorised modes (walking and cycling), transit modes (bus, underground, and e-motor), and driving modes (car and taxi).

Questionnaires were prepared, and several groups of students were organised to interview people at different building types in the three selected cases, asking questions such as how the respondents get to their destination on weekdays, and how long they travelled to their destination. A video was also recorded to count the number of people at the only entrance of the buildings from 7:30 am to 9:30 am as this is the period for people travelling to work. This accurately recorded and then estimated the number of people in the buildings. The following information can be summarised when doing data collection for travel activities:

- Number of people in the community /population density;
- Travel modes and corresponding percentages;
- Average daily travelled distance;
- Travel time and frequency;
- Travel purpose;

2) Emission factors (EFs)

The emission factors, measured in kg/km included, cover popular vehicle categories (car/ taxi, public transport, and e-motor), and this factor is not fixed as the technologies developed. Given the fact that over the past dozen years, China's vehicle technology and fuel quality have improved, the carbon emission factor of transport modes cannot be maintained at the same level and should be corrected. As a result, this research assumes that the carbon emission coefficient decreased by 0.5% annually based on the reference (Liu 2014), for this is more in line with the reality.

Table 3.1 summaries the research methods for this study in data collection, methods, tools and outcomes.

Table 3.1 Summary of research methods

Methods	Tools	Outcomes
Building energy model	Sketch, HTB2 and ViVil	Building energy use and CO_2 emissions
Activities-based transport demand model	Equation	Transport-related CO_2 emissions
Building energy simulation	HTB2 and ViVil	The relationship between building energy consumption and factors
Regression analysis	SPSS 20	The relationship between transport-related CO_2 and modal splits

3.3 Softwares selected in this research

3.3.1 Introduction to selected tools HTB2

HTB2, developed at the Welsh School of Architecture, Cardiff University, is intended to simulate energy and environmental performance of buildings. It was initially programmed for thermal simulation, including fabric conduction, ventilation, heating and cooling systems, as well as the part of the building design process tool (Alexander 2008). The validity and reliability of the software have tested, and it has worked well (Alexander 2003). After a series of improvements, HTB2 is now able to simulate a group of buildings. However, HTB2 is not a simple model, and beginners find it difficult to use it. Users must set up all parameters in each required file gradually, which makes it easy to make mistakes. The complicated setting process possibly affects the accuracy of its simulation result. Furthermore, without a virtual Windows environment and visualisation operation interface, it is hard to define the parameters explicitly. Although there are many disadvantages with HTB2 involved in describing complex models, HTB2 has the best performance for simulation at the urban scale.

HTB2 regards buildings as a series of spaces, which are connected to the outdoor environment by walls, roofs, windows and ventilation paths shown in Fig. 3.3. The calculation mechanism of HTB2 mainly considers heat exchanges from the external climate, heating systems, and a network of incidental heat sources, and the whole process is the dynamic thermal simulation (Lewis and Alexander 1990).

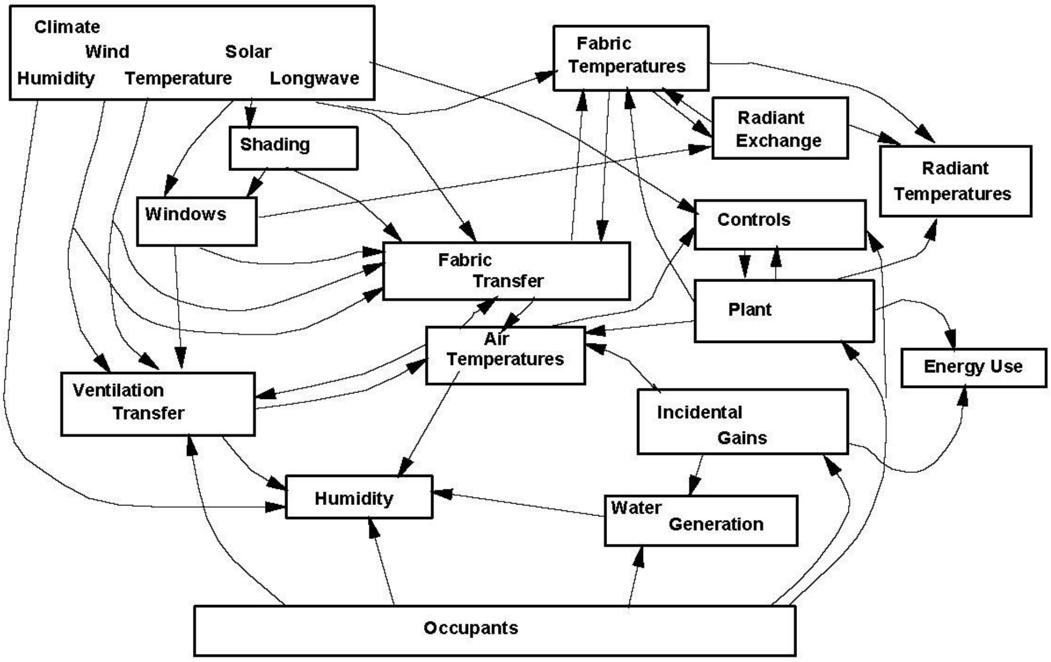


Figure 3.3 Fundamental building processes and interactions
Source: Alexander (2008)

All the parameters of these units should be calculated together based on their time, which can be set between a single minute to a whole year. In short, model builders should decompose a building or spaces first and reorganise them, according to HTB2's hieratical levels (Fig. 3.4 shows). For each level and topic, there are corresponding files to manage the data. Then, HTB2 will calculate these data together and produce a final report.

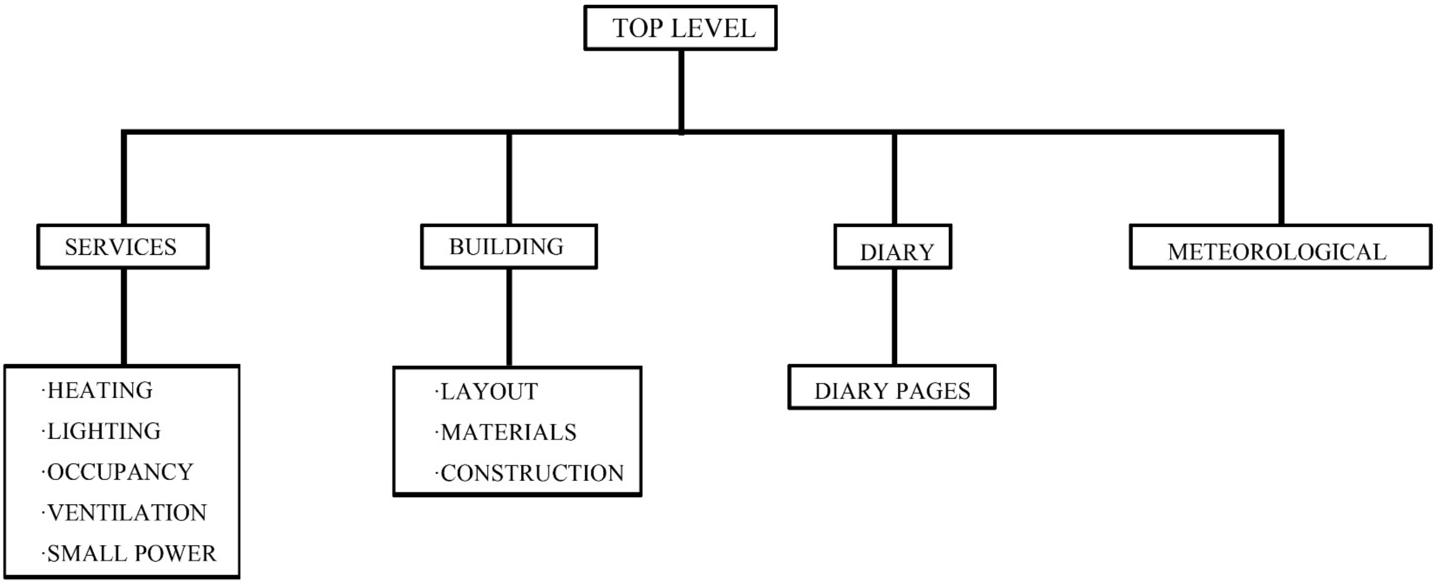


Figure 3.4 HTB2 hierarchical structure

Source：Alexander (2008)

3.3.2 Introduction to selected tools Plug-in VirVil

A VirVil Plug-in (Virtual Village) is a simulated tool for the evaluation of the impact on the sustainable built environment at the urban level (Jones et al. 2011). It uses dynamic simulation at an early stage with simple input data to reduce complication and focuses on the impact on the community, as well as on single buildings. The tool brings current state-of-the-art simulation capabilities to provide the most comprehensive and credible modelling software (Smith et al. 2008). The Plug-in actively considers the relationship between buildings and environment. The VirVil menu in SketchUp is shown in Fig. 3.5, and the calculation of VirVil integrating with SketchUp and HTB2 is shown in Fig. 3.6.

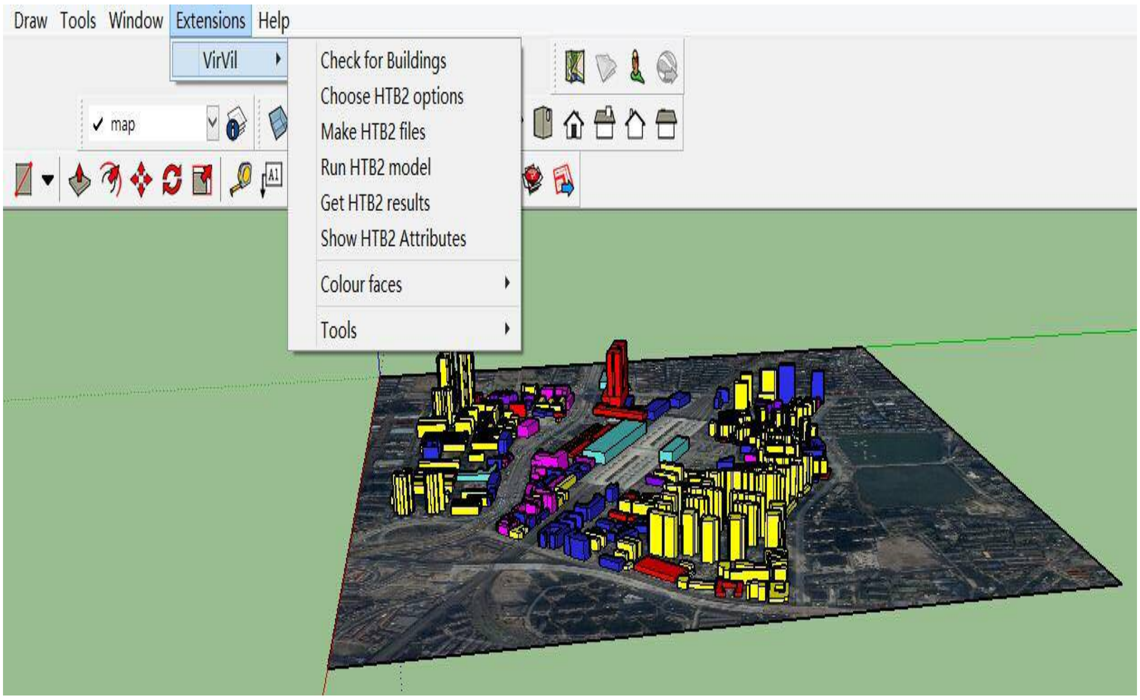


Figure 3.5 The menu of plug-in VirVil in Sketchup

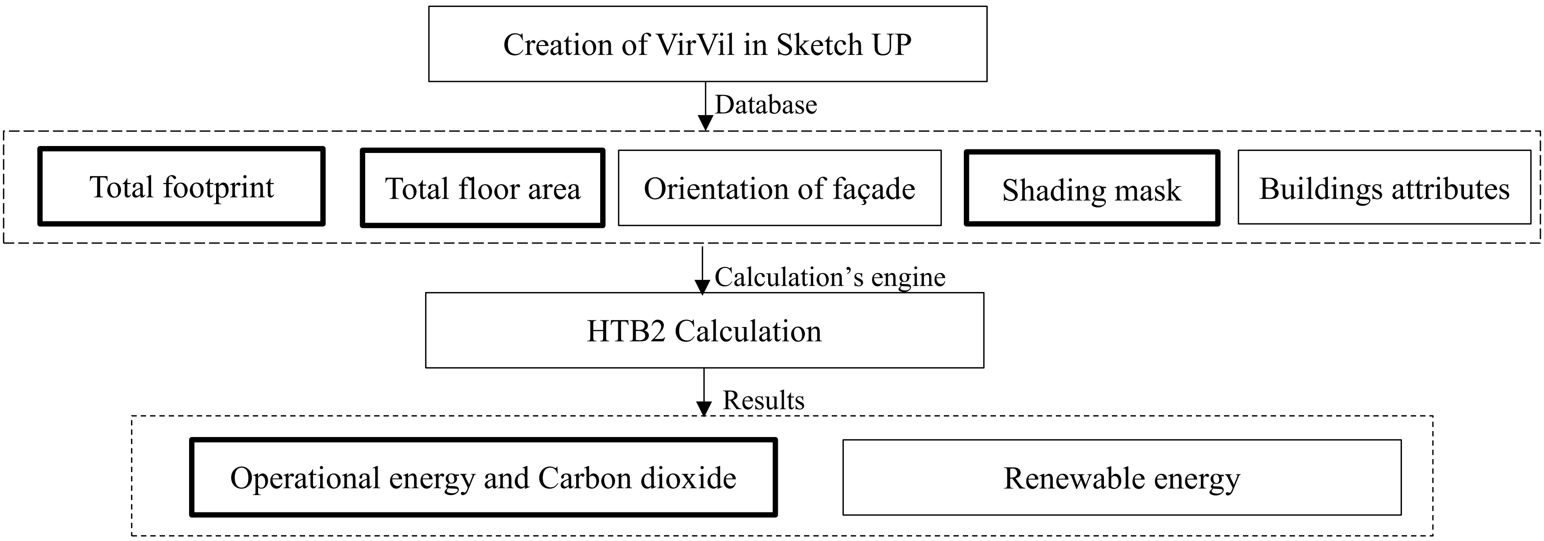


Figure 3.6 Flow diagrams of VirVil integrating with SketchUP and HTB2

3.3.3 Introduction to selected tools SPSS

SPSS Statistics (Statistical Package for the Social Sciences) is a software package used for statistical analysis. It is a powerful statistical tool for providing the descriptive statistics, bivariate statistics, prediction of numerical outcomes, and prediction for identifying groups (Wikipedia 2016a).

In this study, IBM SPSS Statistics 20 is used to perform multinomial logistic regression analysis. The regression model is to examine the relationship between modal splits and three selected factors (socio-economic, travel patterns and self-evaluation), and then the transport-related CO_2 emissions.

3.4 Summary

Through a discussion of the methods involved in the prediction of energy consumption on buildings and transport sector, some important points can be summarised as follows:

Firstly, previous research relating to the prediction of building energy and transport-related CO_2 emissions are examined and analysed. There are mainly two methods: bottom up and top down. The advantages and disadvantages of these two methods are also analysed. Then, methods in this research are also presented, which include building energy model, activities-based transport demand model, modal splits regression analysis, literature analysis, site surveys and questionnaires. Research tools used in this research also vary. These tools are plug-in VirVil, modelling software SketchUp, energy calculation engine HTB2, and regression analysis tool SPSS 20. There are also some challenges in this research, especially in data collection for transport-related carbon emissions.

Chapter 4 Case Studies Introduction —High-density Building Clusters Located around Passenger Railway Station in Wuhan

4.1 Introduction

Chapter Four selects three high-density building clusters around three stations as case studies. **Firstly, these three Cases can represent three different locations: outer city, inner city and new urban districts. Secondly, data collection relating to energy use from buildings and travel activities from the transport sector is much easier to obtain for these three Cases.** The purpose of this chapter is to get a better understanding of the background of three cases before modelling in the following chapter. The information relates to the geographic and climate conditions, and the general built environment development focus on buildings and the transport, all of which can help get a comprehensive understanding of these three case studies.

4.2 The geographic location of Wuhan

Wuhan is in the middle of Hubei Province, as well as the capital city of this province. It is located in the east of Jianghan Plain at the intersection of the Yangtze and Han rivers. Water bodies account for 26.1 % of the total Wuhan land area (Huang and Yin 2015). The Yangtze River and the Han River converge in the centre of the city and divide Wuhan into three parts— Wuchang, Hanyang, and Hankou (Fig. 4.1) — Wuhan's Three Towns. Wuhan is also known as "Jiusheng Tongqu" (the nine provinces 'leading thoroughfare'); it is a major transport hub, with three railway stations (Fig. 4.2), connecting to the major cities in mainland China (Wikipedia 2016b). Aside from this, Wuhan is known as the "City of Lakes" since 166 lakes are distributed around the city. Among them, 43 lakes are in urban areas, and 123 lakes are in the suburbs. Hence, conservation of water resources is a key issue and concern (Li et al. 2010).

Figure 4.1 The city of Wuhan

Source: http://www.china-tour.cn/Wuhan/Wuhan-City-Map.htm

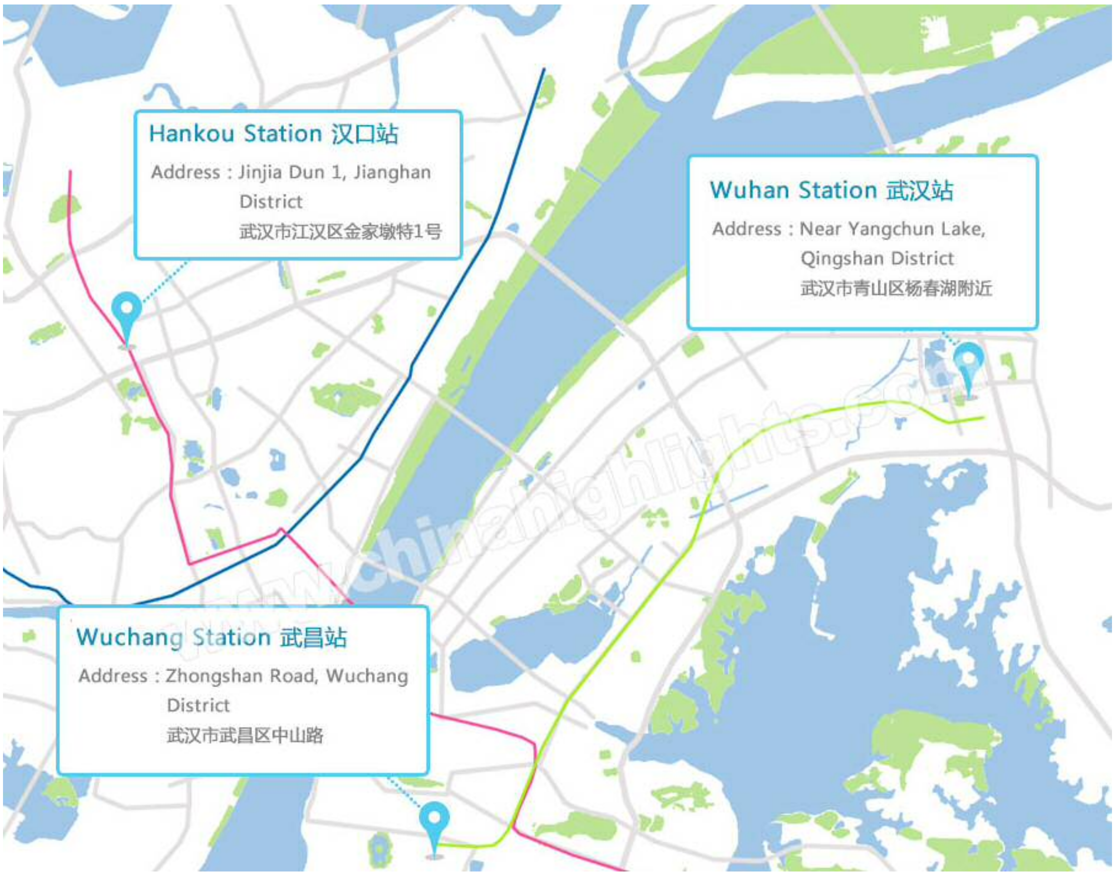


Figure 4.2 The geographical location of the three railway stations in Wuhan

Source: Baidu images

4.3 Climate characteristics in Wuhan

Wuhan is in the hot summer and cold winter zones and experiences a severe climate in summer and winter periods. It is also known as one of the three "furnace cities" in China. It is extremely hot in July and August, as well as freezing during the cold winter period in January.

The average annual temperature of the city is around 18℃, while the lowest average temperature is minus 10 °C in January. The highest temperature usually occurs in July and August and can reach over 40 °C (Wu 2015). Figure 4.3 shows the daily dry bulb temperature in Wuhan city. It can be seen that without the effect of direct solar radiation, the temperature can reach almost 40 °C. As for the total monthly solar radiation, the peak value happens in July with more than 650 MJ/m^2 (Fig. 4.4 shows). When it comes to the relative humidity, the monthly value is range from 60 % to 80% as shown in Fig. 4.5.

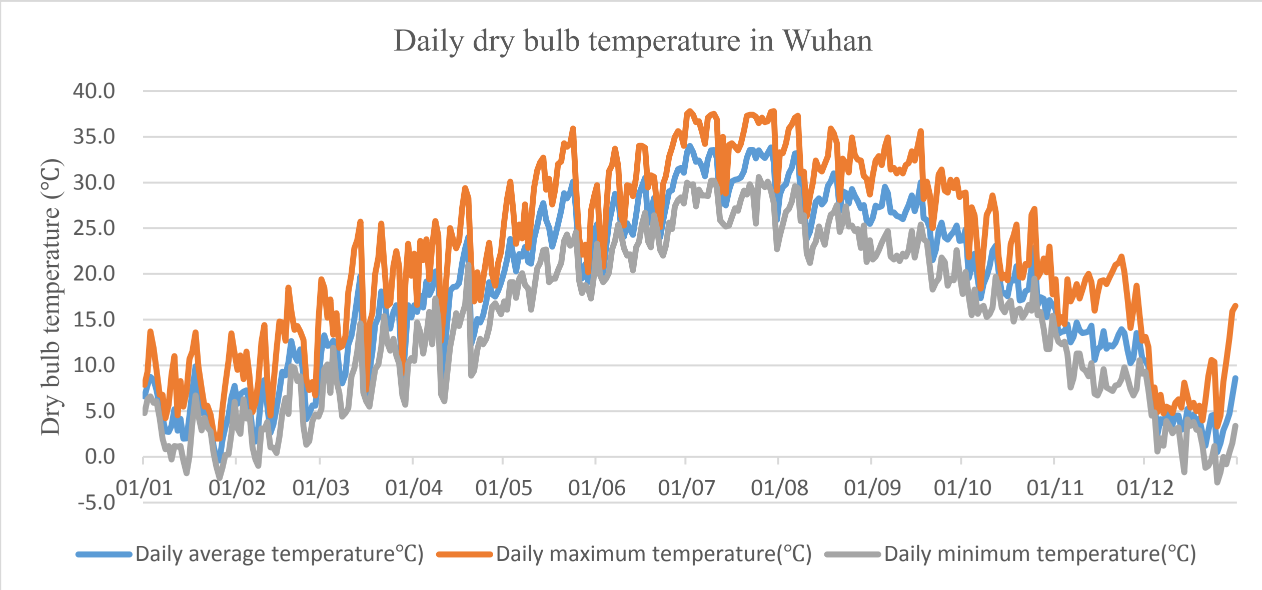


Figure 4.3 The statistics of daily dry bulb temperature in Wuhan

Source: Special weather dataset for China's building thermal environment analysis

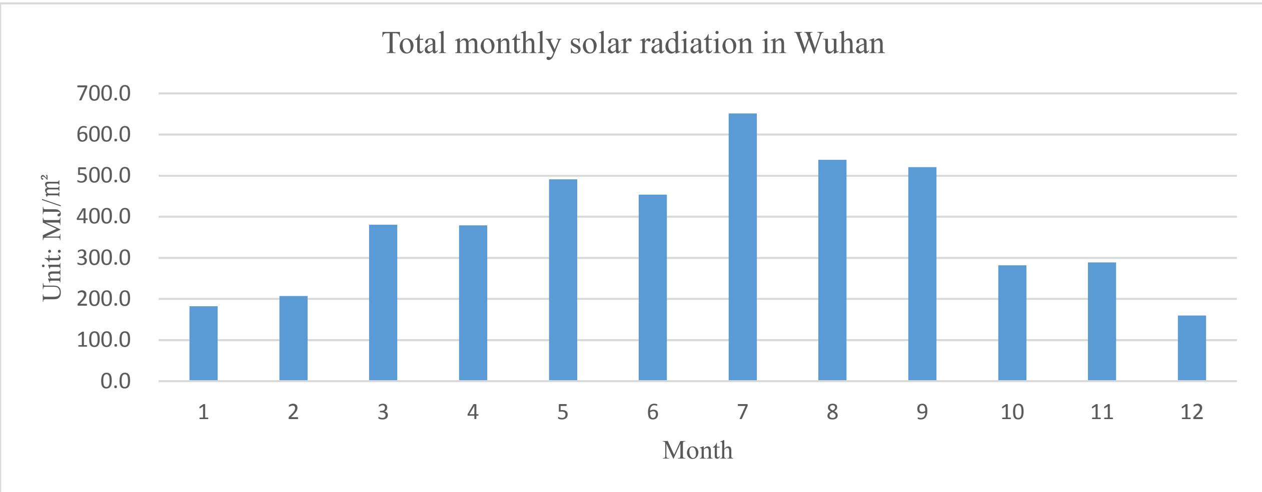


Figure 4.4 Total monthly solar radiation in Wuhan

Source: Special weather dataset for China's building thermal environment analysis

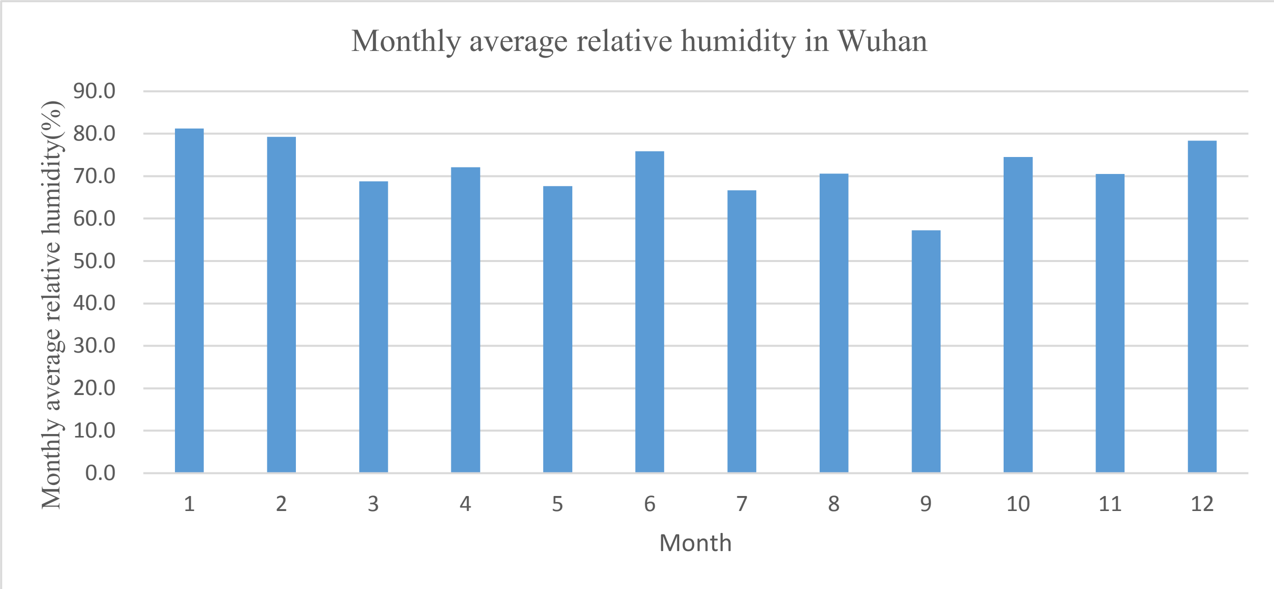


Figure 4.5 Relative humid in Wuhan

Source: Special weather dataset for China's building thermal environment analysis

Moreover, Wuhan is one of the most important cities in central China for its location. Due to it being one of the most major transport hubs in central China, Wuhan is increasingly attracting domestic and international investment from other areas in the world, transforming the city into one of the largest economic centres and low carbon city in China.

4.4 General characteristics of the built environment in Wuhan

The built environment is the physical form of surroundings. It includes land use patterns, large and small scale built and natural features (e.g., architectural details and urban planning.), and the transport system (the facilities and services that link one location to another) (Forsyth et al. 2008; Brownson et al. 2009). The term is used when referring to those surroundings created:

- for humans,
- by humans, and
- to be utilised for the human activity.

The pressures of high population density and urbanisation bring many problems for the built environment in Wuhan city. Massive energy consumption and CO_2 emissions, heavy traffic volume, and unsustainable buildings constructed from the 1970s to the 1990s are easily found around the stations. Selected important issues are discussed in this research including energy consumption and CO_2 emissions from buildings and transport, and the land use development in the built environment in Wuhan city.

Firstly, there is high electricity demand due to a large number of population and the increasing level of construction in Wuhan city, especially in residential buildings. Population distribution among these three districts from the year 2011 to 2016 is shown in Fig. 4.6. There is the largest population in Wuchang district. Besides, according to the survey, the areas with the highest residential use and commercial buildings for business also have high energy demand.

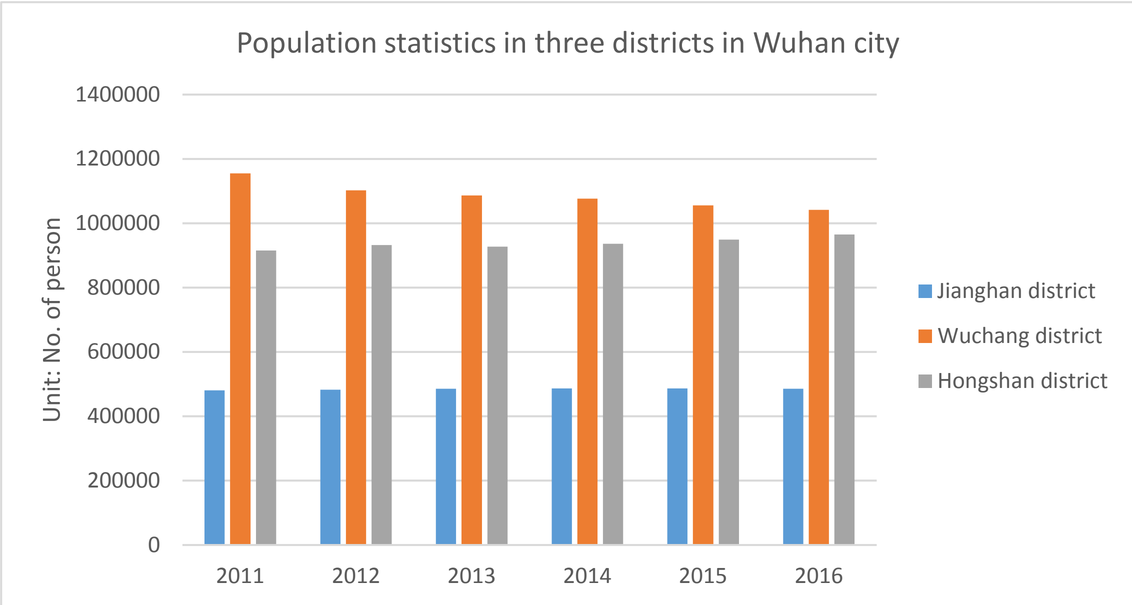


Figure 4.6 Population statistics in three districts in Wuhan city

Source: Statistics Bureau of Wuhan Municipality (2017)

Notes: Wuchang Station is in Wuchang District; Hankou Station is in Jianghan District; Wuhan Station is in Hongshan District but closer to Qingshan District

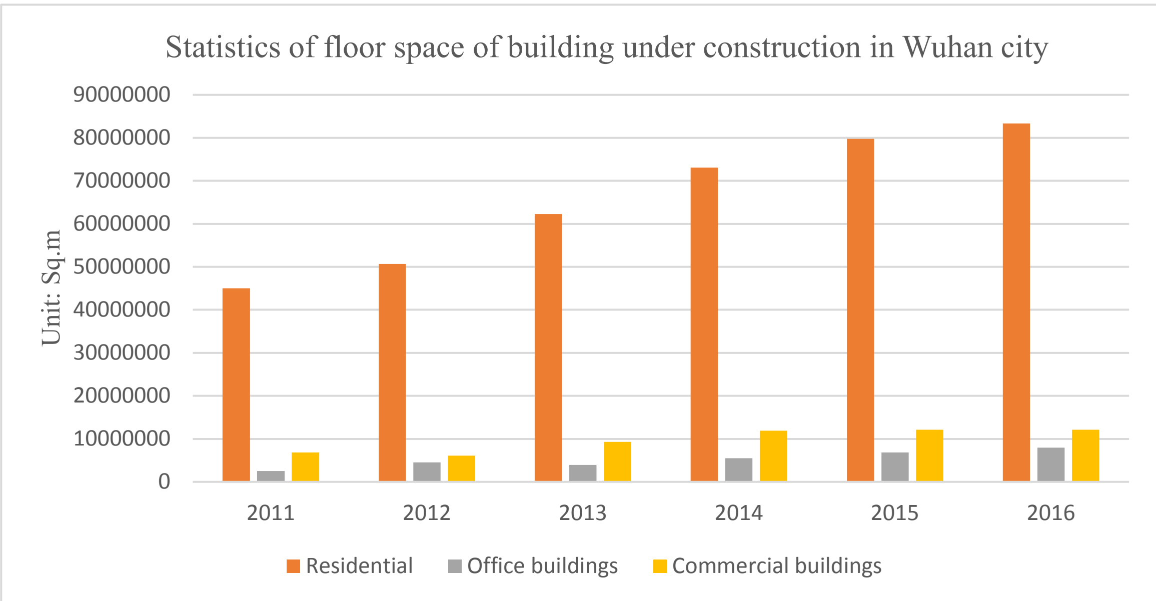


Figure 4.7 Floor spaces of residential construction in Wuhan city

Source: Statistics Bureau of Wuhan Municipality (2017)

As Figure 4.7 shows, there was a steady increase in residential buildings under construction in Wuhan from over 45 million square metres in 2011 to over 80 million square metres in 2016. In contrast, a tiny increase was observed in commercial buildings, and the total floor space of residential buildings was largely more than that of public buildings. In short, the increase in floor space of buildings and larger population contribute to the high-energy demand in cities.

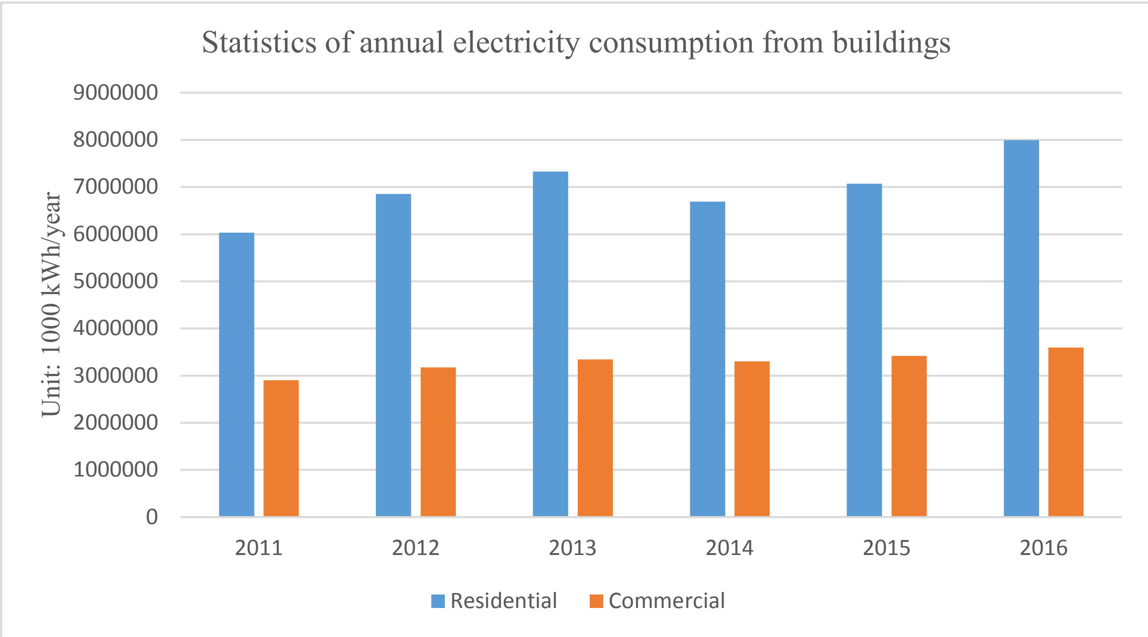


Figure 4.8 Electricity consumption from commercial and residential use in Wuhan city
Source: Statistics Bureau of Wuhan Municipality (2017)

Figure 4.8 illustrates that there was an upward trend in the electricity consumption from residential buildings from the year 2011 to 2016，but it was steady for commercial buildings (referring to commerce, hotel and catering service). Moreover, the total annual electricity consumption from residential buildings was largely higher than that of commercial buildings, by more than two times by the year of 2016 due to the larger floor area of residential buildings than commercial buildings. More importantly, the annual electricity consumption in residential and commercial buildings can be calculated from Fig. 4.8 and Fig. 4.9, which ranged from 92 to 134 kWh/ m^2 / year in residential buildings and 278 to 426 kWh/ m^2 / year in commercial buildings from the year of 2011 to 2016.

Secondly, transport is one of the main elements which has a strong relationship to the increase in carbon dioxide emissions. From the year 2011 to 2016, the number of cars in Wuhan more than doubled from 0.95 million to 2.30 million (Statistics Bureau of Wuhan Municipality 2017) (Fig. 4.9 shows). And this trend will continue in the future. By contrast, there was a steady decrease in motorcycles. In a short, cars increase and motorcycles decrease for personal use have played a significant role in transport-related carbon dioxide emissions.

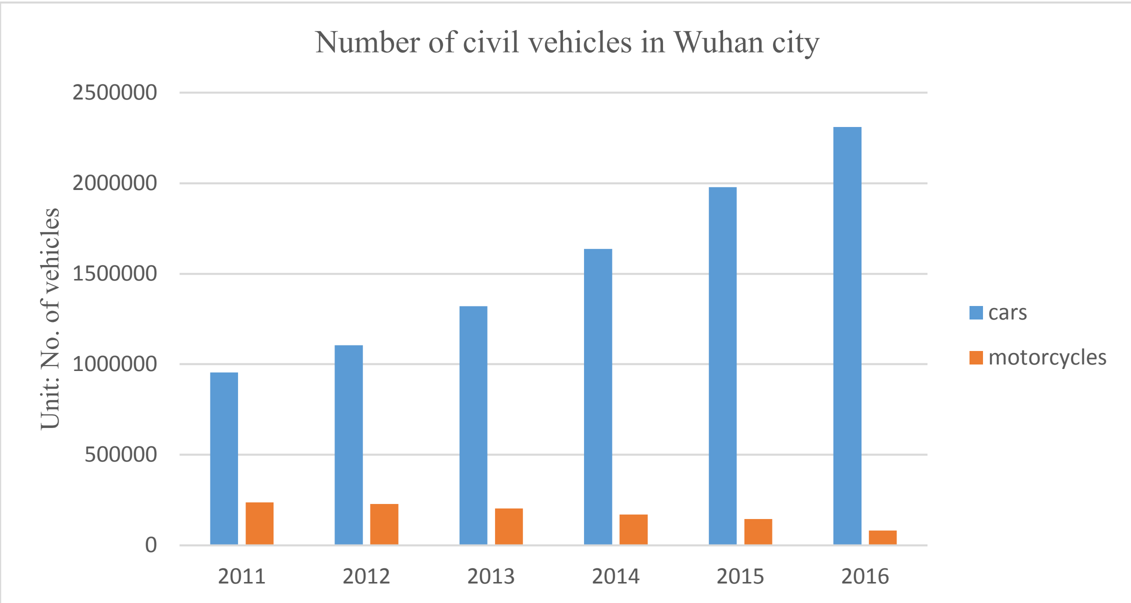


Figure 4.9 Number of civil vehicles in Wuhan City

Source: Statistics Bureau of Wuhan Municipality (2012-2017)

Thirdly, land usage is another issue involved in controlling the size of a city and the strength of the urbanisation, especially around the stations. The land use around the stations has a feature of "3-Ring" spatial structure pattern in site selection, and the construction of high-speed rail stations is shown in Fig. 4.10. The Ring I, ranging from

1 to 1.5 km^2, is the area that provides direct services to passengers such as hotels and restaurants. Ring II further extends 3 to 5 km^2 outwards and is a functional sprawling and supplemental area to Ring I, with commercial and office use, while Ring III is the indirect backup area that provides the service to residential use (Hao 2008). The functional characteristics of the surroundings in high-speed rail terminal feature within Ring I, transit to Ring II, and evolve into Ring III. Hence, the emphasis on planning development and transport management should be placed in Rings I and II.

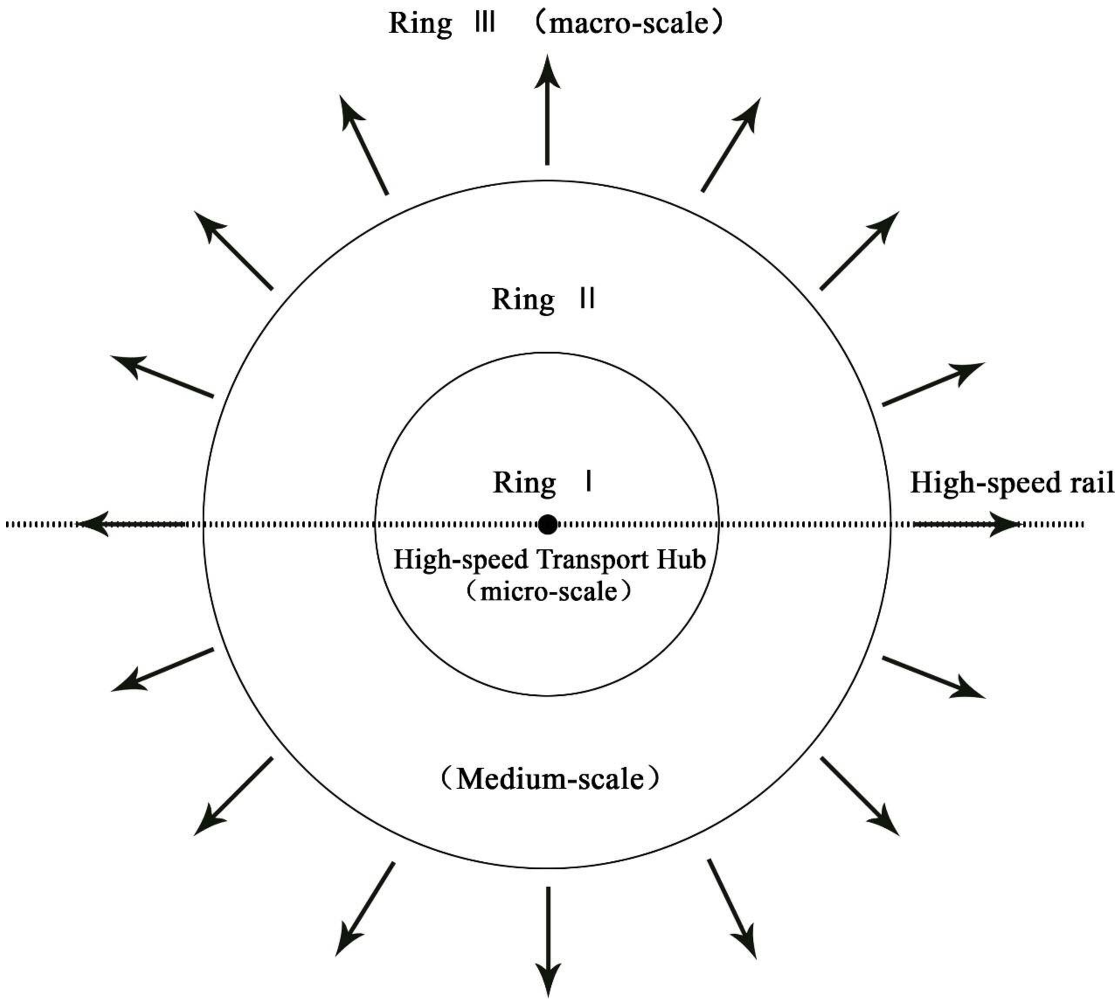


Figure 4.10 "3-Ring" spatial structure pattern

Figure 4.11 and Figure 4.12 are typical examples of the land development around the Hankou station. The surroundings of the stations feature commercial and office use and are linked with mixed-use development. This feature maximises land use through resource sharing, minimises travel demands, and makes the journey more convenient.

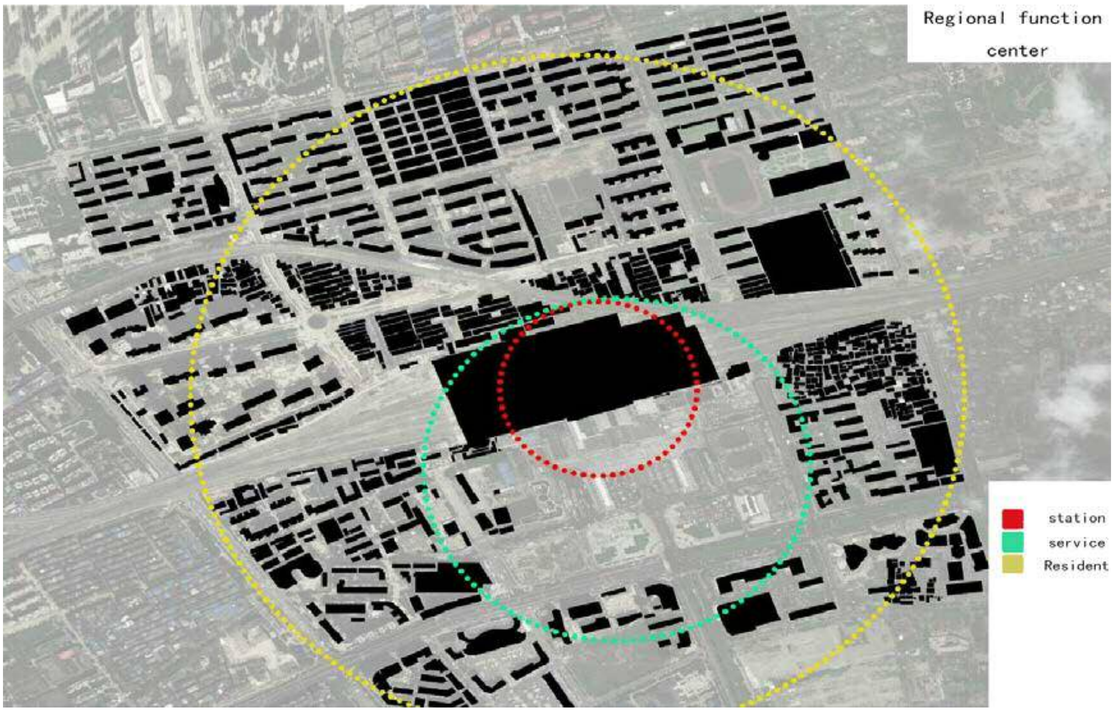


Figure 4.11 3-Ring land use development around Hankou Station

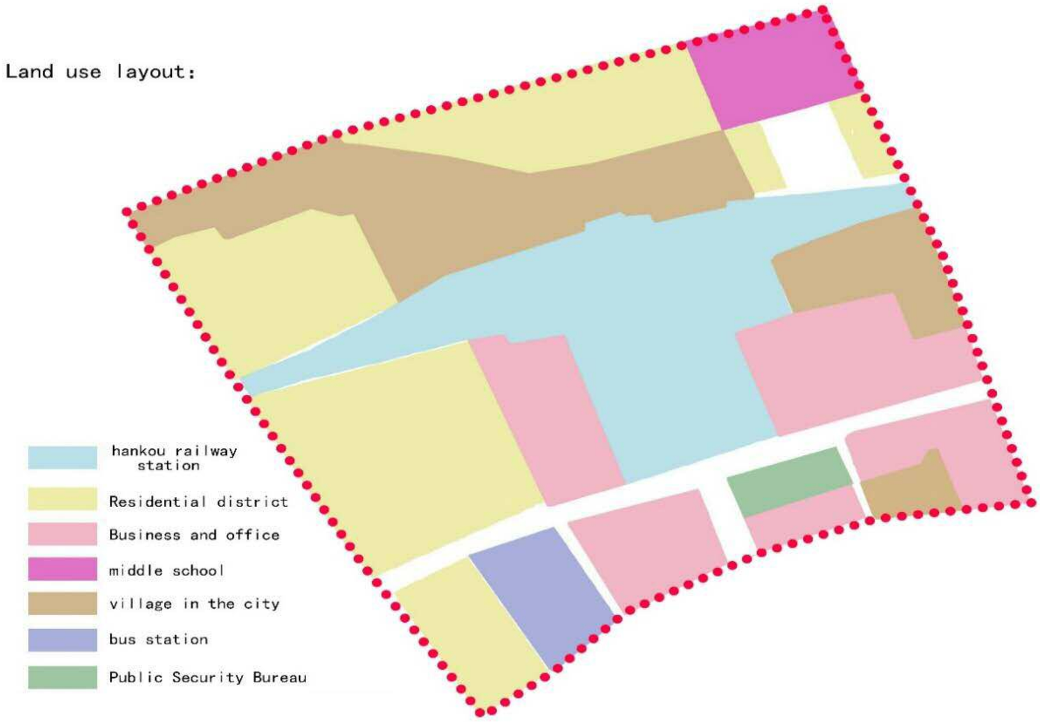


Figure 4.12 Land use around the Hankou Railway Stations

Table 4.1 provides the general characteristics of the 3-Rings development around the stations. It analyses the function, scale, and area affected by each ring.

Table 4.1 Characteristics analysis within each ring around the stations

Ring	Ring I	Ring II	Ring III
Distance to the station (km)	0.5~0.8	<1.5	>1.5
Functions	Traffic service	Direct influence	Indirect influence
Influence of station on spatial layout	Direct control	Direct influence	No direct correlation
Major impact aspects	Road and land layout; function and land price	Function, population, land development	No direct correlation
Boundary definition	Adjacent block, the borderline clearly defined	The surrounding neighbourhood, boundary weakening	Not directly reflected in the function, boundary opening
Highly correlated features	Catering, hotel, business, offices.	Businesses, offices, residence, education, and industry	No direct correlation

4.5 Summary

This chapter mainly introduces the characteristics of three selected cases around Wuchang railway station, Hankou railway station, and Wuhan station. These features encapsulate the geographic and climatic conditions in Wuhan, and the general built environment development (buildings and the transport). It shows that the energy consumption and carbon dioxide emissions from buildings and transport have an upward trend due to the increase of construction in buildings and the rise of vehicles numbers. Moreover, the pressure on the built environment is growing with the convenience brought by urbanisation and the increasing vehicles available. In short, the rising trend of building energy consumption and massive transport carbon dioxide emissions can hinder the low carbon city development in Wuhan.

Chapter 5 Modelling Building Clusters Energy Consumption in Three Case Studies

5.1 Introduction

Chapter Five focuses on answering the question:

"for the fundamental research related to the quantification of energy consumption from building clusters, what kinds of methods can be used, and how can technical tools be used to quantify carbon dioxide emissions from building clusters?"

China has attached great importance to developing low carbon cities around HSR (high-speed railway) stations recently, called high-speed railway new urban districts. The related research and actions are still at an initial stage and tend to revolve around energy-efficient buildings and sustainable transport planning. Although there are some limited evaluation systems and specific green building regulations that have been officially published by adopting existing regulations and systems from developed countries, such as the UK and US, a lack of fundamental research involved in China's practical situation still exists. For example, the large discrepancy in energy use from different building types and high carbon emissions from transport seriously hinders research involved in low carbon development.

Therefore, this chapter aims to apply technical tools to simulate energy consumption from different building types (residence, office, commerce) around three stations by combining HTB2, VirVil Plug-in, and the modelling tool SketchUp. The simulation is based on building energy model to understand and analyse the energy performance of different building types. Additionally, the results explain differences of energy consumption of various building types. The outline of this chapter is presented in Fig.

5.1.

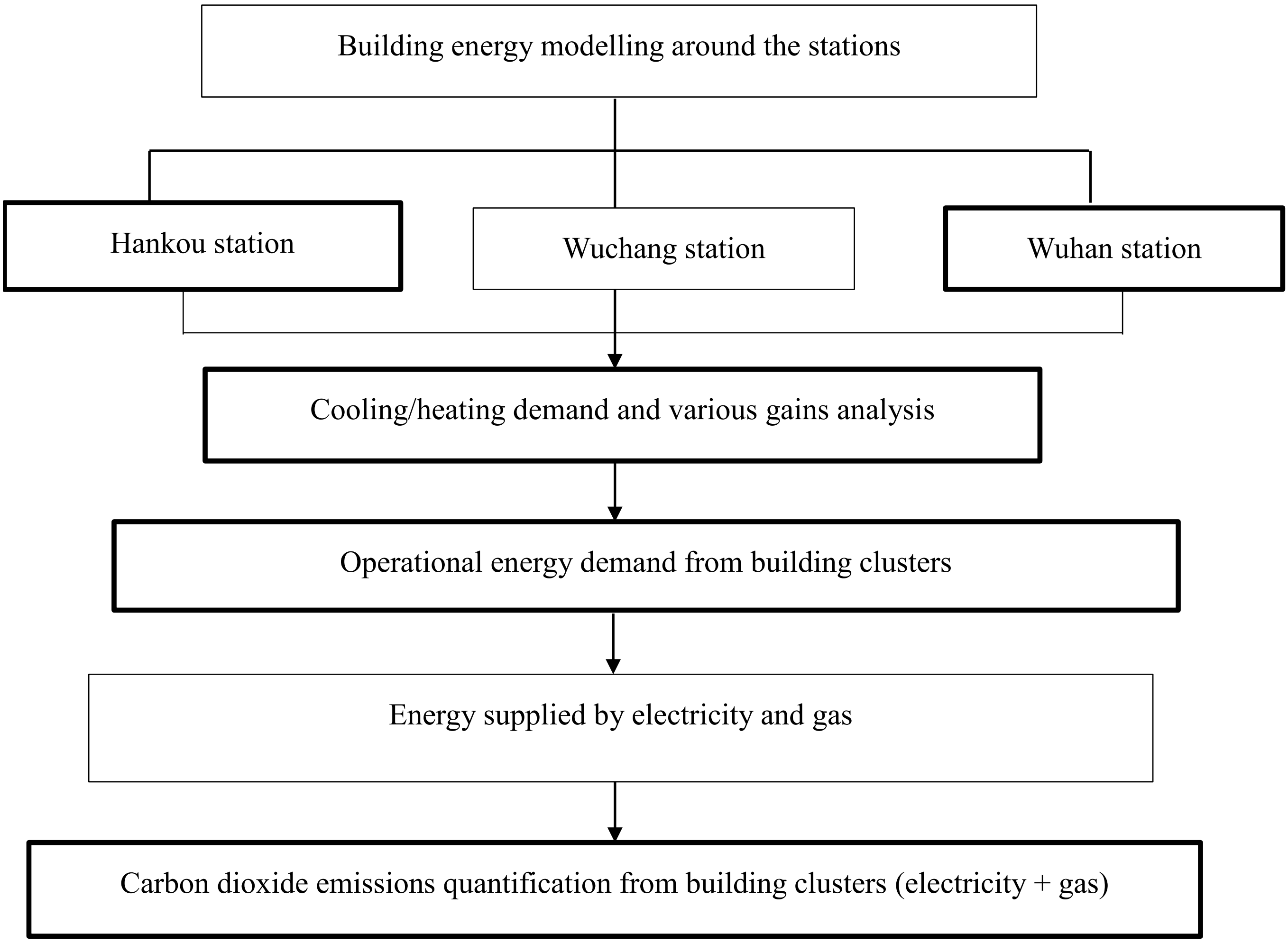


Figure 5.1 The framework of this chapter

5.2 Case Study 1: Modelling building clusters around the Hankou station

5.2.1 Basic description in the study area

The study area of Case 1 is on the south-west of the Hankou station, within around one kilometre of the station (Fig. 5.2). According to the investigation, there are four types of buildings: residential, commercial, office, and hotel buildings. Residential buildings consist of the Donghang Residential community and the Hejiadun community. Public buildings in the Hejiadun community include the Wuhan Bureau of Education Building, the Wuhan Building of Science, and the Jiangfeng Building. The survey finds that most of the buildings in this study area are for residential use, representing 47%, followed by office purposes (36%), and then commercial purposes (14%), as shown in Fig. 5.3. Moreover, most of the residential buildings were built before the year 2000, while the public buildings were built at around the year 2005. The floor area with each building type is presented in Table 5.1.

Figure 5.2 The geography of the study area from Case 1

Source: Google Earth

Table 5.1 The floor area of different building types around Hankou station from the investigation

Building classification		Area (㎡)	Area（Total）㎡
Households		75073	75073
Public	Commercial	22187	84206
	Hotel	4881	
	Office	56938	

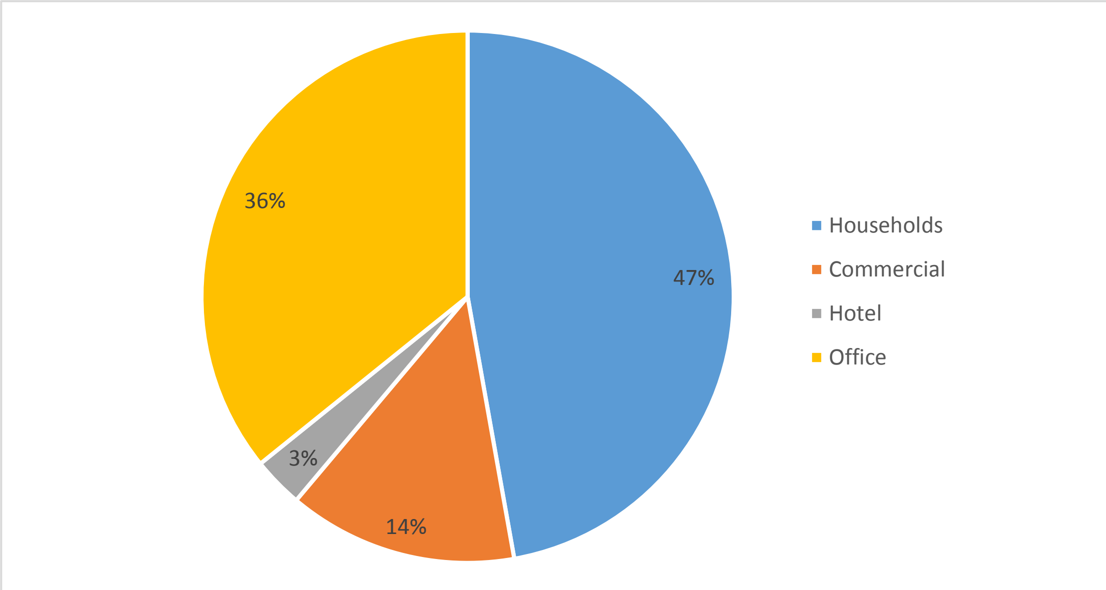


Figure 5.3 The proportion of building classification from the investigation

According to the survey, there are 536 households with around 1760 people for residential use. Other three public buildings are around 2054 people. Therefore, the total population is around 3800. The detailed information of the population in the study area is summarised in Table 5.2.

Table 5.2 The statistics of the population in the study area

	Number of people	Equation to calculate	Estimated methods description
Residential buildings	1761	426*3*93.2%+210*3*90%	No. of households × persons per households × Occupant rate
Wuhan Building of Science	1000	Data provided by the Property	
Jiangfeng Building	624	13*3*2*8	Storeys × No. of households per staircase× No. of units × persons per household
Wuhan Bureau of Education Building	430	Data provided by the official website	

For the Donghang Residential Community, there are three residential buildings built in the year 1997, with 210 households in this community, and the occupancy rate is about 90%. According to the on-site survey, it has been found that these three buildings were the same ways for the construction of the façade, glazing, etc. The U value for the external walls is very high, as these buildings were not regulated by energy-saving standards at the time of the construction. As a result, the electricity consumption, especially during the summer and winter periods, is considerably higher according to the reports from residents.

For the Hejiadun Community, the function of the different buildings is diverse, including hotel, residential, and elderly community services use. However, the majority are for residential use. There are 426 households in the community, with 93.8% occupancy rate according to the survey. The remaining buildings are public buildings for office and commercial uses. The detailed data collected for this study area are summarised in Table 5.3.

Table 5.3 The statistics of the study area around Hankou Railway Station   Source: on-sit

ID	Name	Building classification	Storeys	Area （Total） ㎡	
1	Donghang Community	Household	7	6990	
2			7	6931	
3			7	8618	
4	Hejiadun Community	Household	7	9328	
5			7	10044	
6			7	6563	
7		Hotel	8	**4881**	
8		Household	9	7199	
9			7	4532	
10		Household	4	2510	
11	Wuhan Education Bureau	Office	12	**12141**	
12	Wuhan Building of Sci and Tech	Office	20	44797	20
13	Hejiadun Apartment	Household	12	12358	
14	Jiangfeng Building	Commercial	13	22187	25

5.2.2 Simulation conditions setting for building clusters around Hankou station

The simulation conditions include the meteorological conditions, the materials, construction of the buildings, glaze ratio of the buildings, and the interior design condition such as the set of services and diary. This section presents the meteorological conditions, internal heat gains, heating and cooling schedule, and building construction and materials in the HTB separately.

Meteorological conditions

The meteorological parameters are derived from the typical meteorological year (TMY) of Wuhan city and are used for energy simulations with HTB2 on the energy models to measure the energy consumption of cooling/heating from thirteen buildings. Meteorological data is available from the weather data of the EnergyPlus website (http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm), which was extracted and converted from a “. epw” file into a “.met” HTB2 under logical file by using the HTB2 Weather File Software.

Internal heat gains

The internal heat gains are closely related to lighting, small power, and occupancy. The contributions of heat gains from lighting, small power, and occupant in buildings cannot be ignored as those heat gains have a big impact on an overall cooling and heating demand, and thus it is necessary to calculate their heat output. The heat generated by occupants depends on everyone’s level of activity. Table 5.4 shows the heat output rate of human bodies for various activities (Bansal et al. 1994).

Table 5.4 Heat production rate in a human body

Source: Bansal et al. (1994)

Activity	**The rate of heat production (w/m^2)**
Sleeping	35
Resting	45
Sitting, Normal office work	55
Typing	85
Slow walking (3 km/h)	110
Fast walking (6 km/h)	140

Lighting is also taken as one of the internal heat gains. A large portion of the energy used for lighting is emitted as heat, and the remainder is emitted as light, which is then converted into heat. Consequently, the total number of lamps in buildings when in use, must be considered as internal heat gains. Another source of heat gains is due to small power (televisions, computers, etc.), which should also be included due to their heat output. Figure 5.4 illustrates the interaction of outdoor and internal heat gains of buildings.

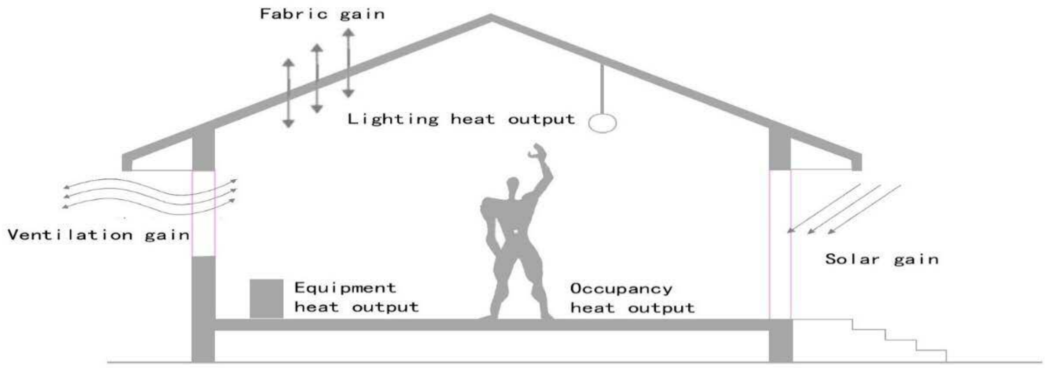


Figure 5.4 Heat exchange processes between a building and external environment

Source: Lin (2013)

Due to the lack of official benchmarks for internal heat gains in China at present, this research estimates the internal heat gains of buildings based on CIBSE Guide A (2015) and related Design Standards for Energy Efficiency of Residential and Public buildings in China. The general use of an office building is taken as an example, with an average density of office buildings at 10m^2 per person according to Design Standard for Energy Efficiency of Public Buildings (MoHURD 2015). The corresponding internal heat outputs from a typical office building can be checked in the CIBSE Guide A (2015) in Table 5.5

Table 5.5 Benchmark values of internal heat gains for general office use in the UK
Source: CIBSE Guide A (2015)

Occupant density (m^2/Person)	Sensible heat gains (W/m^2)			Latent heat gains (W/m^2)
	Lighting	people	Equipment	people
8	12	10	20	7.5
10	***12***	***8.35***	***17.5***	***6.25***
12	12	6.7	15	5

Although the guide does not give the value of the internal gains when the occupant density is 10 m^2/person, an estimate of this value can be interpolated from the given data. This yield a value for heat gains in the office building as 45 W/m^2.

For residential buildings, the corresponding internal heat gains can be estimated to be 5 W/m^2 according to the Design Standard for Energy Efficiency of Residential Buildings in the Hot Summer and Cold Winter Zone (MoHURD 2010, P_{19}). For commercial and hotel buildings, these heat gains can be defined as in Table 5.6

Heating and cooling

Wuhan is in hot summer and cold winter zone. The operational schedule of heating and cooling periods can be determined from the *Design Standard for Energy Efficiency of*

Residential Buildings in Hot Summer and Cold Winter Zone (2010), and *Design Standard for Energy Efficiency of Public Buildings (2015)*. The detailed information for this is outlined in Table 5.6:

Table 5.6 Heating and cooling schedule

<table>
<tr><th>Building type</th><th colspan="2">Heating/cooling schedule</th><th>Setpoint (℃)</th><th>Heat gains (W/m^2)</th><th>Air changes per hour</th></tr>
<tr><td rowspan="2">Residential</td><td>Heating</td><td>08/Nov—04/Mar of the following year</td><td>18</td><td rowspan="2">5</td><td rowspan="2">1.0</td></tr>
<tr><td>Cooling</td><td>6/May—8/Sep</td><td>26</td></tr>
<tr><td rowspan="2">Office</td><td>Heating</td><td>08/Nov—04/Mar of the following year</td><td>20</td><td rowspan="2">45</td><td rowspan="2">2.0</td></tr>
<tr><td>Cooling</td><td>6/May—8/Sep</td><td>26</td></tr>
<tr><td rowspan="2">Commercial</td><td>Heating</td><td>08/Nov—04/Mar of the following year</td><td>18</td><td rowspan="2">50</td><td rowspan="2">2.5</td></tr>
<tr><td>Cooling</td><td>6/May—8/Sep</td><td>25</td></tr>
<tr><td rowspan="2">Hotel</td><td>Heating</td><td>08/Nov—04/Mar of the following year</td><td>22</td><td rowspan="2">20</td><td rowspan="2">2.0</td></tr>
<tr><td>Cooling</td><td>6/May—8/Sep</td><td>25</td></tr>
</table>

Notes: Heating/cooling schedule refers to the Design standard for energy efficiency of residential buildings in hot summer and cold winter zone (2010); cooling/heating setback refers to the design standard for energy efficiency of public buildings (2015); air changes refer to the guidance of design standard for energy efficiency of public buildings (2007).

Operational Schedule

The operational schedules, i.e. the running time of heating and cooling systems, lighting, small power, ventilation, and occupants' activities during the period of use for the simulation, were defined through practical investigation and the national standards. Furthermore, the operation schedules in commercial buildings do not stop at the weekends. The detailed information for the different buildings type is outlined in Table 5.7.

Table 5.7 Interior condition and diary setting for different building classifications

Source: The design standard for energy efficiency of residential buildings in hot summer and cold winter zone (2010); the design standard for energy efficiency of public buildings (2015)

<table>
<tr><th colspan="2"></th><th>Residential building</th><th>Office building</th><th>Commercial building</th><th>Hotel building</th></tr>
<tr><td>Heating/cooling</td><td>Setpoint & operational schedule</td><td>Mon-Fri 00:00 -- 08:00&18:00--24:00 Sat-Sun 00:00-24:00 18/26℃</td><td>Mon-Fri 07:00 18:00；20/26℃</td><td>Mon-Sun 08:00-- 21:00；18/25℃</td><td>Mon-Sun 0:00- 24:00；22/25℃</td></tr>
<tr><td rowspan="2">Internal gains（lighting, occupants, and small power）</td><td>Heat gains</td><td>5 W/㎡</td><td>45W/㎡</td><td>50W/㎡</td><td>25W/㎡</td></tr>
<tr><td>Operational schedule</td><td>Mon-Fri 00:00- 08:00&18:00- 24:00；Sat-Sun 00:00-24:00</td><td>Mon-Fri 08:00-18:00</td><td>Mon-Sun 09:00-21:00</td><td>Mon-Sun 0:00-24:00</td></tr>
<tr><td rowspan="3">Ventilation</td><td rowspan="2">Weekday</td><td>0.5,1.0,1.0, 26℃</td><td>0.5,2.0,2.0,26℃</td><td>0.5,2.0,2.0,26℃</td><td>0.5,1.0,1.0,26℃</td></tr>
<tr><td>00:00-08:00&18:00- 24:00 ON</td><td>07:00-18:00 ON</td><td>08:00-21:00 ON</td><td>00:00-24:00 ON</td></tr>
<tr><td>Weekend</td><td>00:00-24:00 ON</td><td>OFF</td><td>08:00-21:00 ON</td><td>00:00-24:00 ON</td></tr>
</table>

Building Construction and Materials

The building layout, glazing ratio, location of buildings, as well as the site shading, which is affected by the surroundings and building orientation, are all modelled in SketchUp and defined in HTB2 through the VirVil Plug-in. The construction materials for building components and their thermal properties are specified in separate files used during the simulation run. Construction materials of the building components include roof construction, external and internal walls, internal floors and ceilings, ground materials, and the materials used in external windows. Since most of the buildings in the study area were built in the 1990s (especially for residential use), and all their façade constructions are very simple. As a result, their U value is much higher than the national standards' level. However, there are some upgrades in the construction of public building, especially for the exterior walls. It was assumed that buildings within the same category have a similar construction although there are little differences as they are constructed in different ages and have different functions. As a result, there were at least two construction files– residential and public files – as shown in Table 5.8.

Table 5.8 The real construction details for different building types around Hankou station

Building Types	Construction	U-Value（W/m²/℃）	Building Materials	Thickness（mm）
Residential building	Exterior Wall (From Outside to Inside)	1.42	gravel	10
			cement mortar	15
			red brick	240
			cement mortar	20
	Interior Wall	1.61	cement mortar	20
			red brick	200
			cement mortar	20
	Exterior Window (From Outside to Inside)	5.4	glass	4
	Floor-Ceiling (From Top to Bottom)	3.46	marble	10
			cement mortar	25
			Ferro concrete	100
			cement mortar	20
	Ground (From Top to Bottom)	1.41	marble	10
			cement mortar	25
			C_{20} fine aggregate concrete	100
			compacted clay	500
	Roof (From Top to Bottom)	1.02	cement mortar	30
			sand	25
			asbestos tiles	6
			cement mortar	20
			aerated concrete block B06	150
			Ferro concrete	120
			lime and cement mortar	20

Building Types	Construction	U-Value（W/m²/℃）	Building Materials	Thickness（mm）

Office, commercial, and hotel buildings	Exterior Wall (From Outside to Inside)	0.85	granite	20
			Cement mortar	30
			FH inorganic foam insulation board	30
			Red brick	240
			Cement mortar	20
	Interior Wall	1.61	Cement mortar	20
			Red brick	200
			Cement mortar	20
	Exterior Window (From Outside to Inside)	5.32	glass	6
	Floor-Ceiling (From Top to Bottom)	3.35	marble	20
			Cement mortar	30
			ferroconcrete	100
			Cement mortar	20
	Ground (From Top to Bottom)	1.40	marble	20
			Cement mortar	30
			C20 fine aggregate concrete	100
			Compacted clay	500
	Roof (From Top to Bottom)	1.02	Bitumen felt	6
			Cement mortar	20
			Light concrete screed	20
			Aerated concrete block	150
			ferroconcrete	120
			Lime and cement mortar	20

Table 5.9 Glazing ratio setting for four building categories

Building type	Glazing ratio
Office	50%
Commercial	
Hotel	
Residential	30%

5.2.3 Simulation of building clusters

Following the building classifications defined in the previous section, there are four prototypes in this case relating to commercial, residential, office, and hotel. The physical dimensions of buildings are based on Google Earth images. The real construction, regular diary, and heating and cooling schedule were recorded through the on-site survey. Building cluster energy modelling from SketchUp 2015 is presented in Fig. 5.5, and the 3D modelling is shown in Fig. 5.6. Afterwards, the results of the monthly gains are presented in line and bar graphs, respectively.

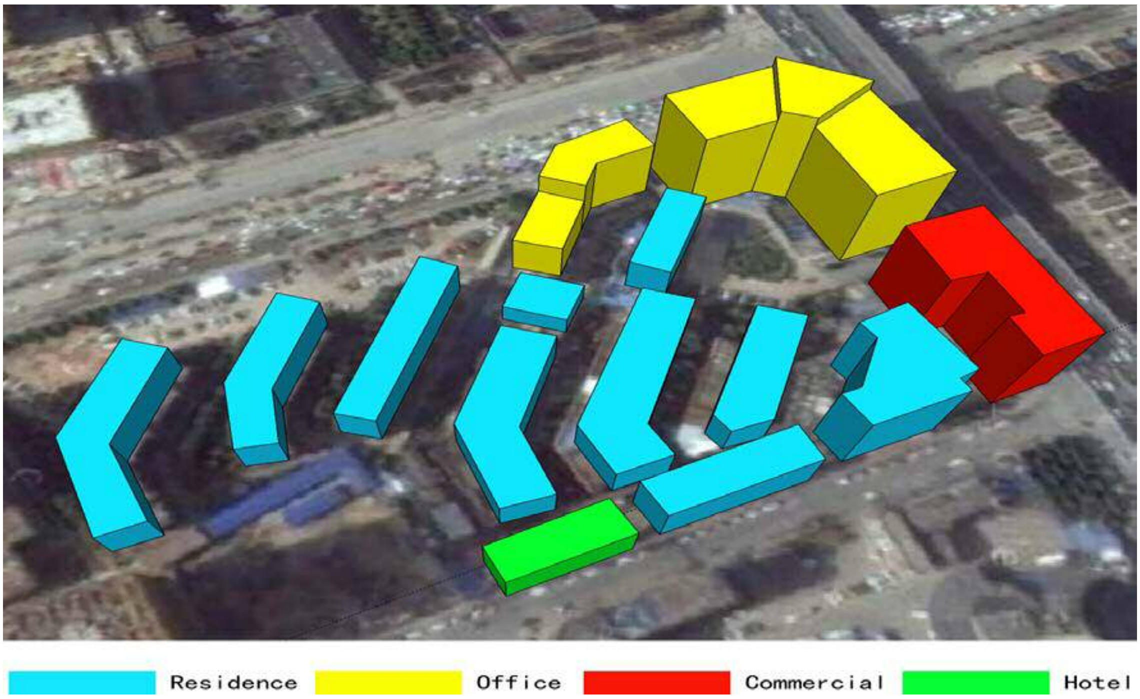


Figure 5.5 Modelling four building types in the study area

Figure 5.6 The 3D model in the study area

Source: http://wuhan.edushi.com/

5.2.4 Results description and analysis

In this section, the results of the simulation are presented classified by building types relating to heater gains, cooler gains, solar gains, incidental gains, fabric gains, and ventilation gains. Then, after the description and analysis of the results, the overall analysis and summary are concluded.

Figure 5.7 and Figure 5.8 show a different monthly gains distribution for all office buildings. More specifically, incidental and solar gains are the major and stable factors to heat buildings throughout the year. Moreover, incidental gains are always markedly more than the solar gains— almost triple the amount of the solar gains. Secondly, the fabric gains fluctuate throughout a year. From September to June, buildings lose heat partially due to the fabric, but the fabric increases the heat retention from June to September, which would increase the cooling demand. Thirdly, ventilation always causes heat loss from buildings to the outside throughout the whole year. Fourthly, the figure shows that there is a significant cooling demand in July, but a lower heating demand in January. In short, the reduction of incidental gains relating to cooling demand should be given priorities.

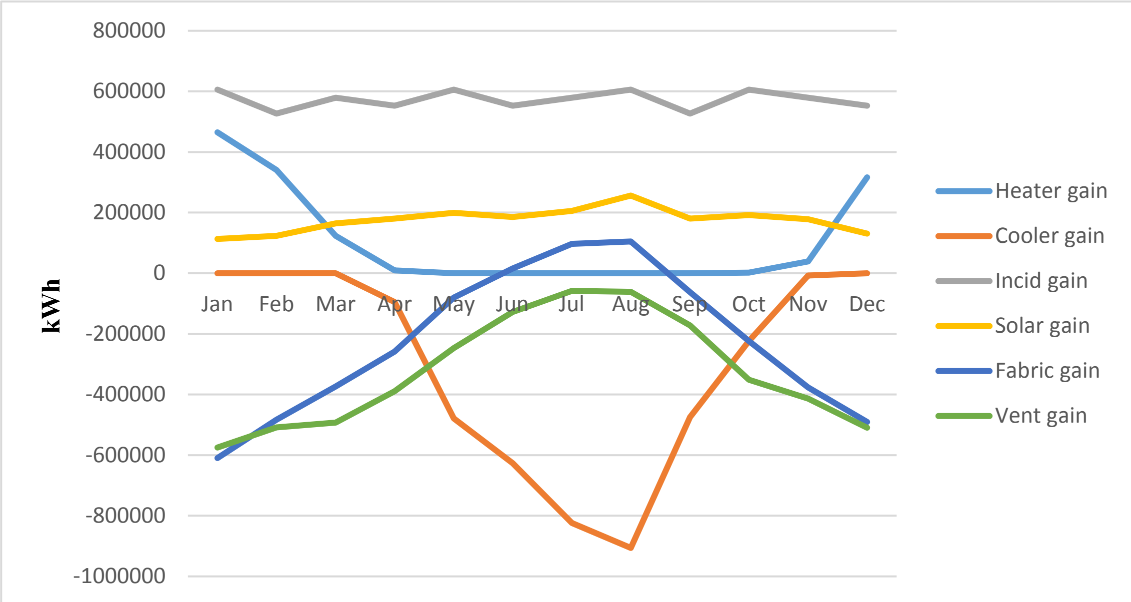


Figure 5.7 The monthly gains from the heater to vent for office buildings

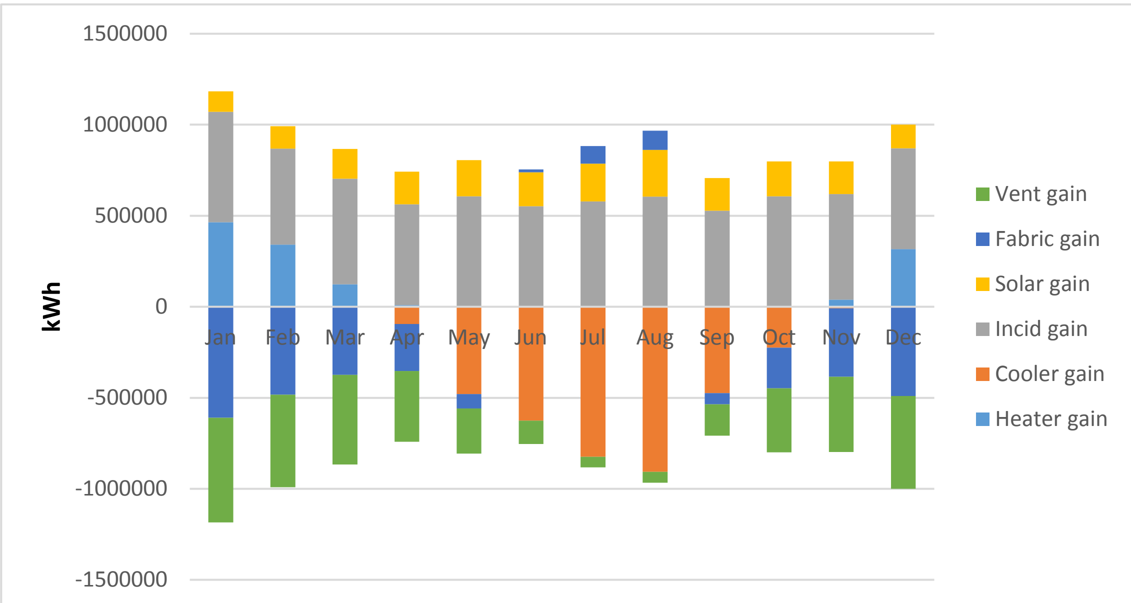


Figure 5.8 The distribution of monthly heat gains from vent to heater for office buildings

Figure 5.9 and Figure 5.10 show that all commercial buildings have different gains distribution during the year. Firstly, incidental and solar gains are the major factors to heat buildings. Moreover, incidental gains are considerably greater than the solar gains. Secondly, the fabric gains are markedly different each month. From September to June, buildings lose heat due to fabric gains but increase heat from June to September. In contrast, the ventilation gains usually cause buildings to lose heat. Thirdly, the figures show that there is substantial cooling demand in July, but less heating demand.

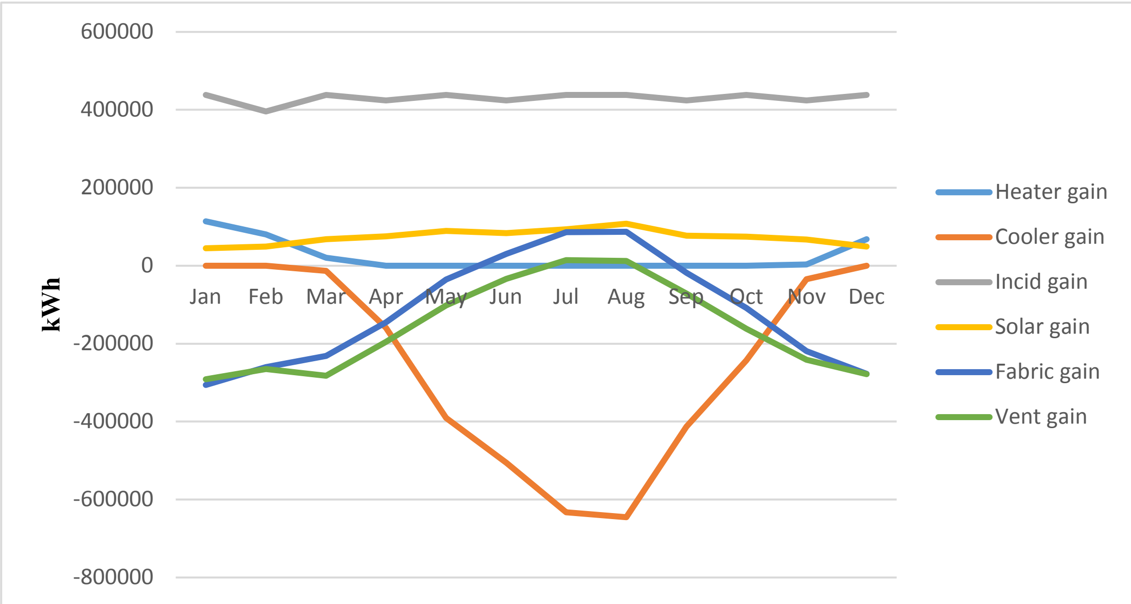


Figure 5.9 The monthly gains from the heater to vent for commercial buildings

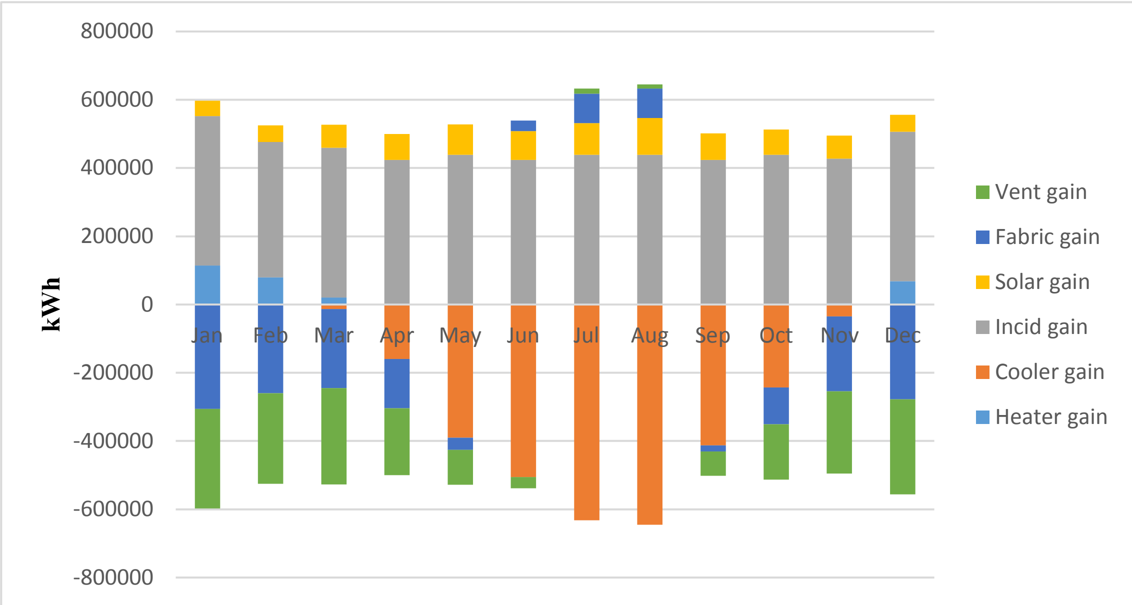


Figure 5.10 The distribution of monthly heat gains from vent to heater for commercial buildings

The following two modelling results (Fig. 5.11 and Fig. 5.12) show different gains in residential buildings. Specifically, incidental and solar gains are the major stable heat sources for buildings, but their effects are almost equal, which is very different from public buildings. Secondly, the fabric gains fluctuate throughout the year. From September to June, the fabric makes buildings lose heats while increasing the total heat from June to September, which would increase cooling demand. In contrast, ventilation always makes buildings lose heats throughout the whole year. Thirdly, the figures show that there is a significant heating demand in December and January, but less cooling demand in July and August. Moreover, the peaking heating demand is markedly higher than the peaking cooling demand. In short, for residential buildings, the reduction of heating demand shows huge potential for energy saving.

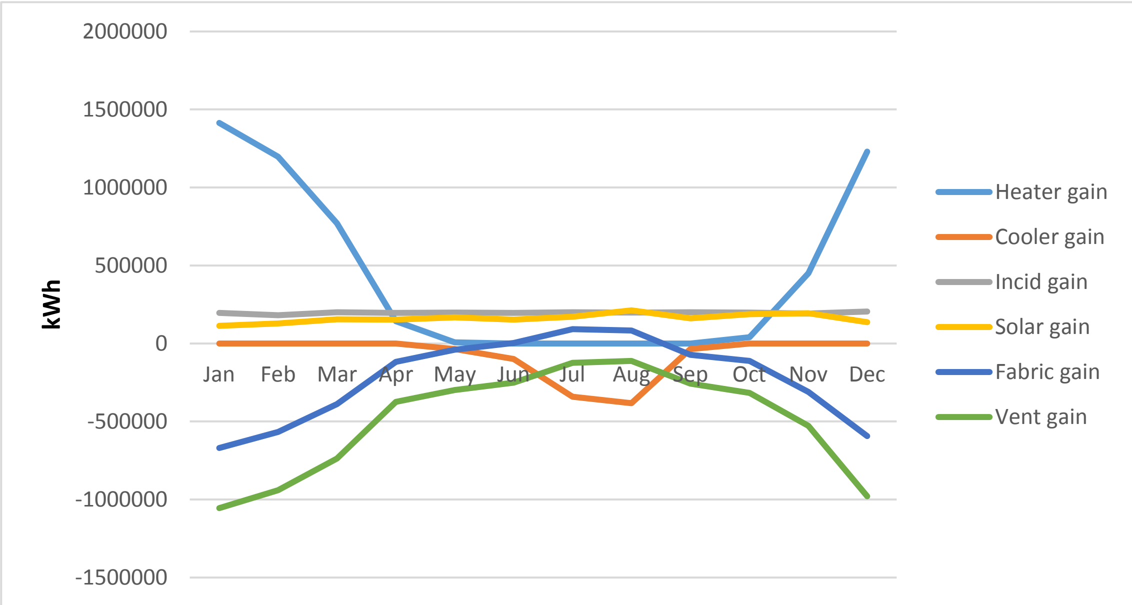


Figure 5.11 The monthly gains from heater to vent for residential buildings

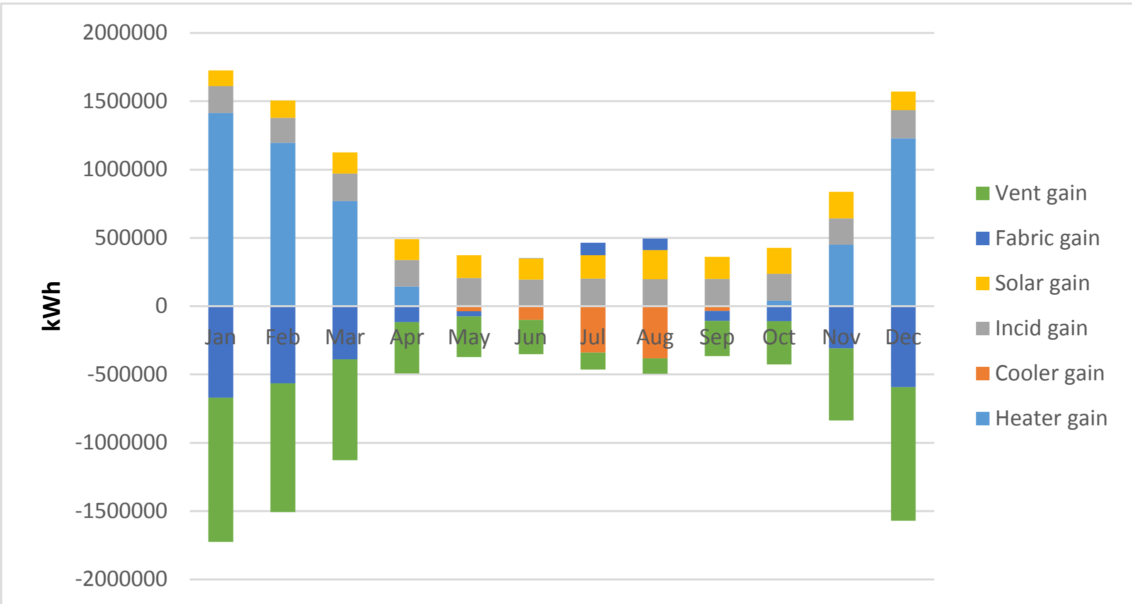


Figure 5.12 The distribution of monthly heat gains from vent to heater for residential buildings

Figure 5.13 and Figure 5.14 show different monthly gains in hotel buildings. Firstly, incidental and solar gains are the major heat source for buildings. Moreover, incidental gains are considerably more than the solar gains. Secondly, the fabric gains fluctuate throughout the year. In contrast, ventilation always makes buildings lose heat. Thirdly, the figures show that there is a significant requirement for cooling in July and August, and less of a requirement for heating. In short, for hotel buildings, reducing incidental gains provides huge opportunities for cutting down energy consumption.

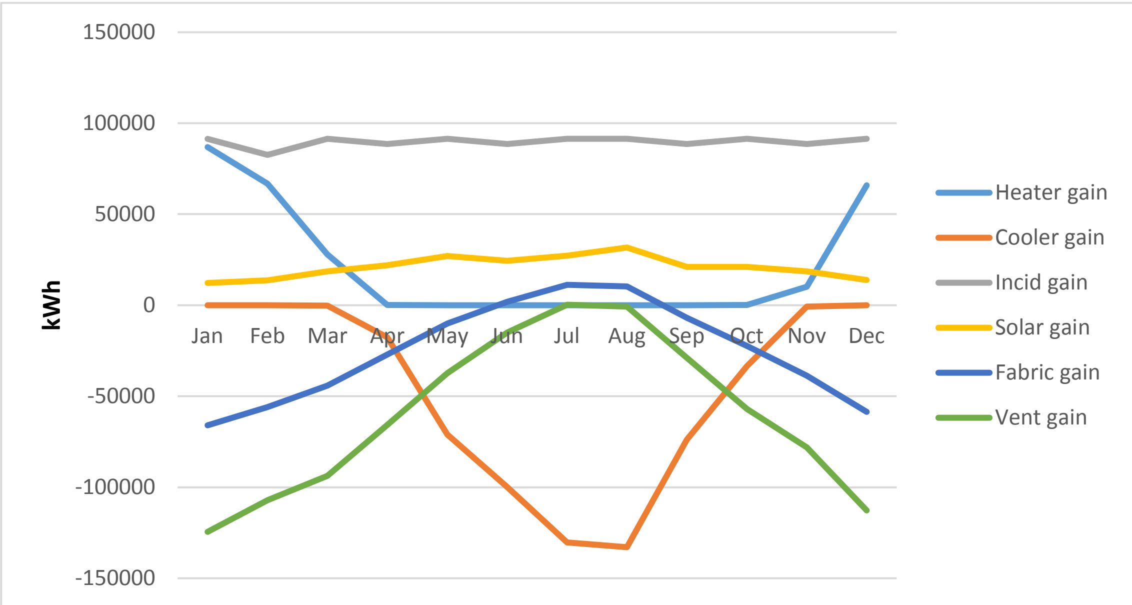


Figure 5.13 The monthly heat gains from the heater to vent for hotel buildings

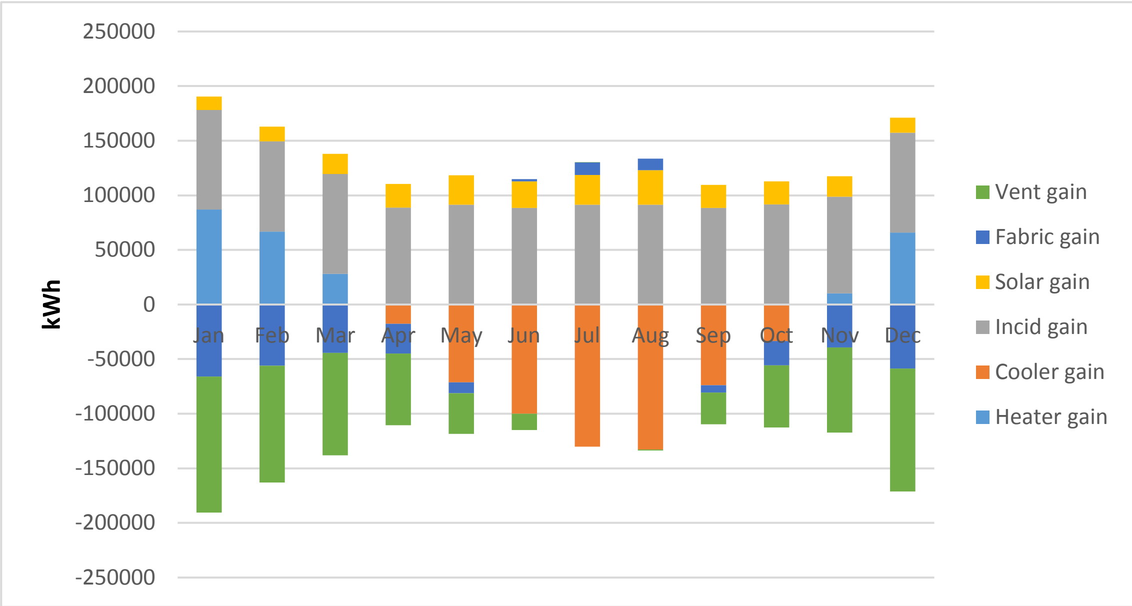


Figure 5.14 The distribution of monthly heat gains from vent to heater for hotel buildings

The modelling results in Fig. 5.15 and Fig. 5.16 show the heat gains from four building types (all buildings together). Firstly, the incidental and solar gains are two principal stable heat sources throughout the year, and the incidental gains always outweigh the solar gains. Secondly, the fabric gains fluctuate dramatically throughout a year. More specifically, from June to September, it becomes the primary heat source, which might increase the cooling demand; from September to June of the following year, the fabric gains make buildings lose heat. In contrast, ventilation gains always have a negative effect to heat buildings during the year. Finally, the figures show that there is a significant cooling demand in July and August, as well as huge heating demand in December and January. Additionally, the highest cooling demand is almost the same as the highest heating demand.

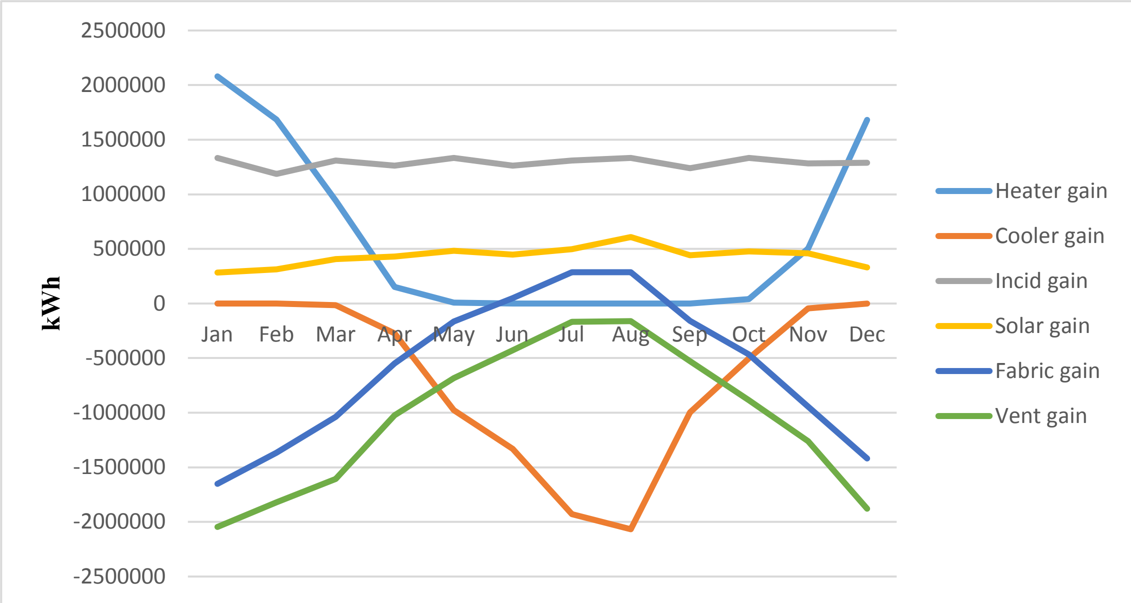


Figure 5.15 The monthly heat gains from the heater to vent for all buildings

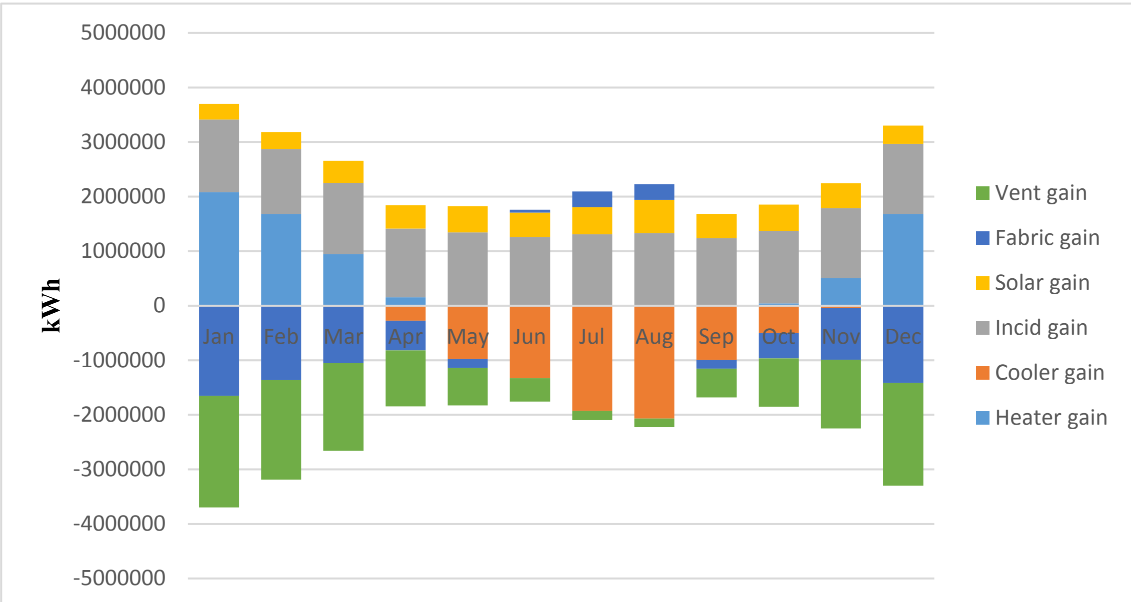


Figure 5.16 The distribution of monthly heat gains from vent to heater for all buildings

The modelling results contribute to understanding the energy performance of buildings, as well as the different gains of four building types from Case 1. Moreover, differences in gains from four building types can be compared and identified. It has shown that the incidental and solar gains are always two stable heat resources to the buildings regardless of their building types and building numbers. The huge cooling demand is needed in commercial, office and hotel buildings, and more heating demand in residential buildings. Reducing the amount of incidental and solar gains can be the biggest opportunities to save energy for buildings.

5.2.5 Energy demand to energy supply

There is a broad range of benchmarks for buildings' operating energy consumption, depending on what is included, such as space heating, cooling, lighting, hot water, and small power. Some benchmarks include all the above aspects, and some only partially cover them. The energy demand relates to the thermal loss associated with heating, cooling, and the power consumption. The energy supply refers to the delivered and supplied energy to the buildings. The difference between energy demand and energy supply relates to the system efficiency and internal loss ratio through transport and distribution. The energy supply is sometimes described regarding the primary energy sources, including the gas, oil, coal, and other fuels associated with electricity generation in the power stations. The carbon dioxide emissions are associated with the primary energy use. Figure 5.17 describes the relationship between energy demand and energy supply.

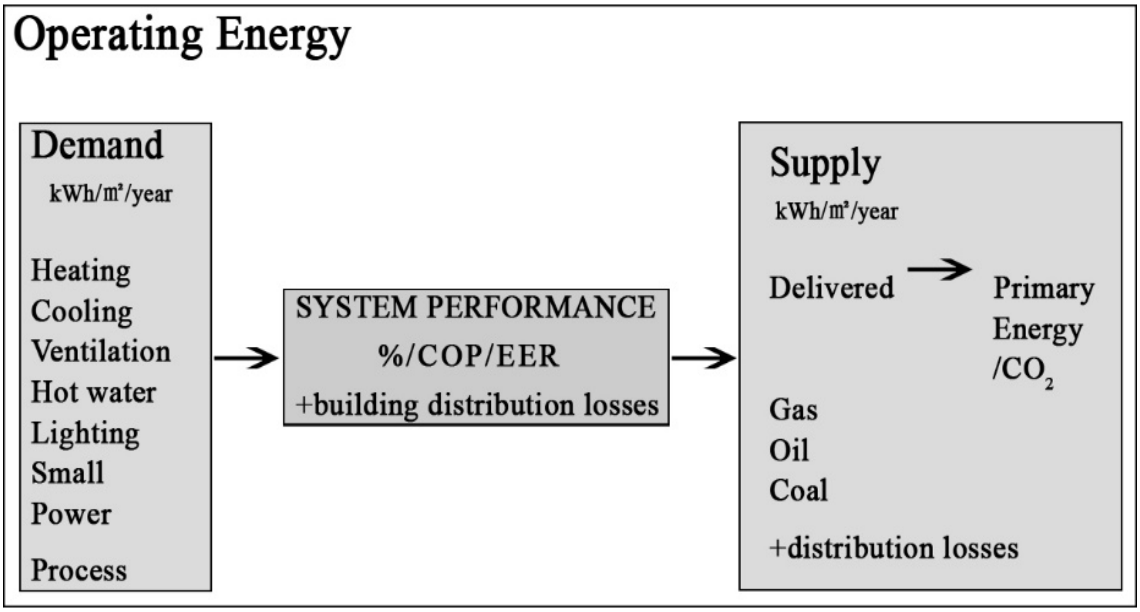


Figure 5.17 The relationship between energy demand and supply

Source: Jones et al. (2011)

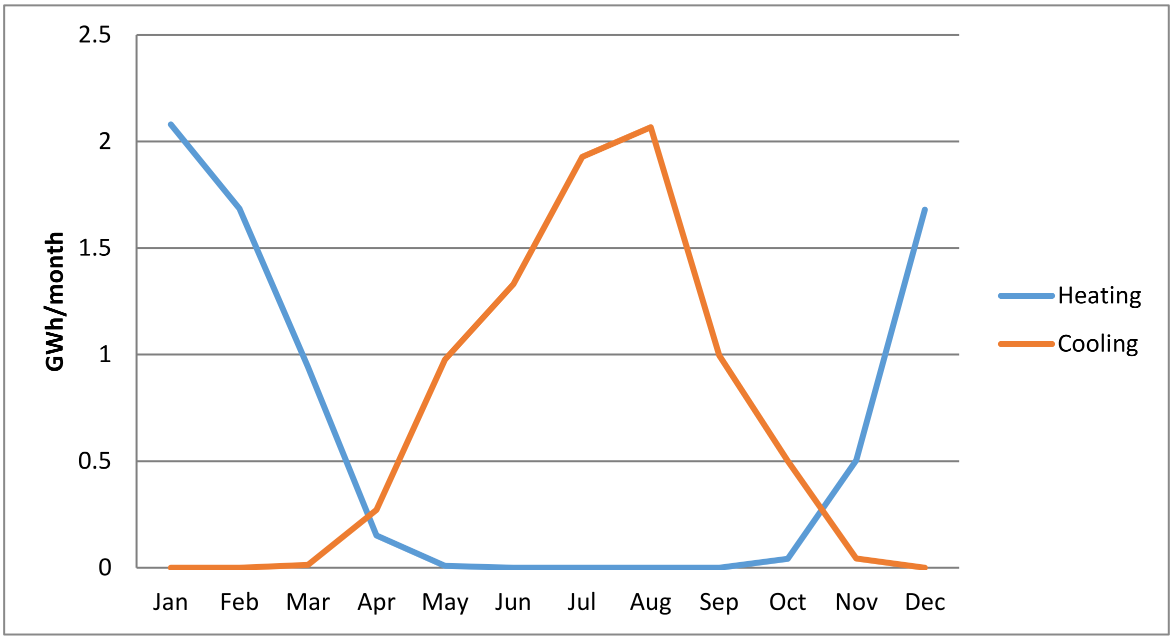


Figure 5.18 The monthly heating and cooling demand for all buildings

Figure 5.18 shows that the monthly cooling and heating demand fluctuates throughout the year in the simulation. There is the highest cooling demand in July and August, while the largest heating demand in December and January as these periods correspond to an extreme weather condition. Moreover, the highest heating demand was almost the same as the highest cooling demand. Detailed information about the annual heating and cooling demand from different buildings is summarised in Table 5.10.

Table 5.10 Summary of annual heating and cooling demand from the simulation

Building type	Building floor area (m^2)	heating demand (kWh/ year)	cooling demand (kWh/ year)	heating demand (kWh/m^2/year)	cooling demand (kWh/m^2/year)
Residential_hankou	76857	5,252,873	-893,206	68	-12
Commercial_hankou	23565	286,454	-3,036,519	12	-129
Office_hankou	58542	1,296,668	-3,636,876	22	-62
Hotel-hankou	4917	257,974	-559,893	52	-114

Table 5.10 illustrates that residential buildings have the highest annual heating energy consumption of around 5.2 GWh/ year, while office buildings have the largest cooling demand (3.7GWh/ year). However, once one considers the building floor area, commercial buildings have the greatest cooling demand, with around 129 kWh/m^2/ year, followed by hotel buildings with 114 kWh/m^2/ year. In contrast, the residential buildings still keep the largest heating demand with about 68 kWh/m^2/ year. In addition, another obvious characteristic is that out of these four building categories; only residential buildings require more heating demand than cooling demand.

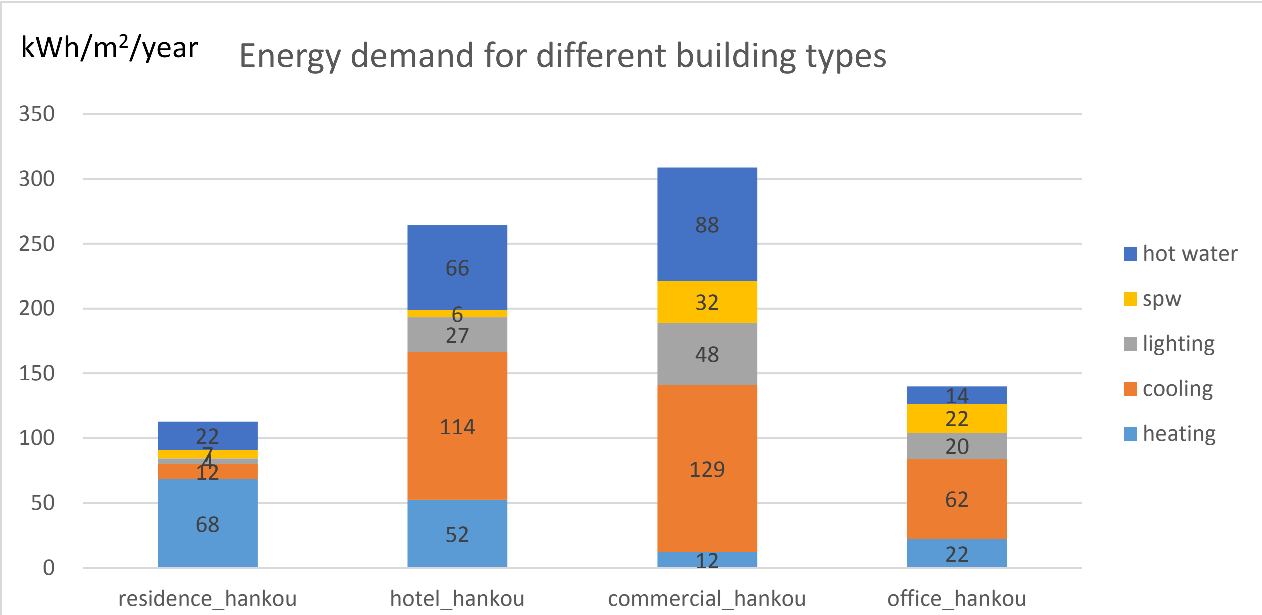


Figure 5.19 Annual energy demand from different building types

Figure 5.19 shows the energy demand from heating to hot water. Different building types have greatly varied in energy demand for services from hot water to heating. For residential buildings, heating was the primary energy demand, while cooling was the primary energy demand for commercial buildings. In summary, commercial buildings have the largest total annual energy demand with 309 kWh/m^2/year. In contrast, residential building has the lowest total energy demand with 113 kWh/m^2/year (Table 5.11).

Table 5.11 The summary of energy demand in each building type

Building type	Energy demand (kWh/ m^2/ year)					
	Hot water	small power	lighting	cooling	heating	Total
Residential	22	7	4	12	68	**113**
Hotel	66	6	27	114	52	**265**
Commercial	88	32	48	129	12	**309**
Office	14	22	20	62	22	**140**

Based on the data of energy demand from each component in Table 5.11, electricity supply can thus be predicted according to Table 5.12 by the power ratio, energy systems efficiency and energy sources. In this research, the system efficiency sets at 3 for cooling, and 2.8 for heating.

Table 5.12 Power ratio and system efficiency used for heating and hot water（electricity supply）

		Heating	Hot water
Residentail_hankou	Power ratio	1	0.7
	System Efficiency	2.8	0.8
Commercial_hankou	Power ratio	1	0.4
	System Efficiency	2.8	0.8
Office_hankou	Power ratio	1	0.6
	System Efficiency	2.8	0.8
Hotel_hankou	Power ratio	1	1
	System Efficiency	2.8	0.8

Figure 5.20 and Table 5.13 presents the annual electricity supply. It shows that commercial and hotel buildings have the highest electricity supply, standing at 186 kWh/ m^2/ year and 191 kWh/ m^2/ year respectively. They are markedly high than that of office and residential buildings (88 kWh/ m^2/ year vs.62 kWh/ m^2/ year).

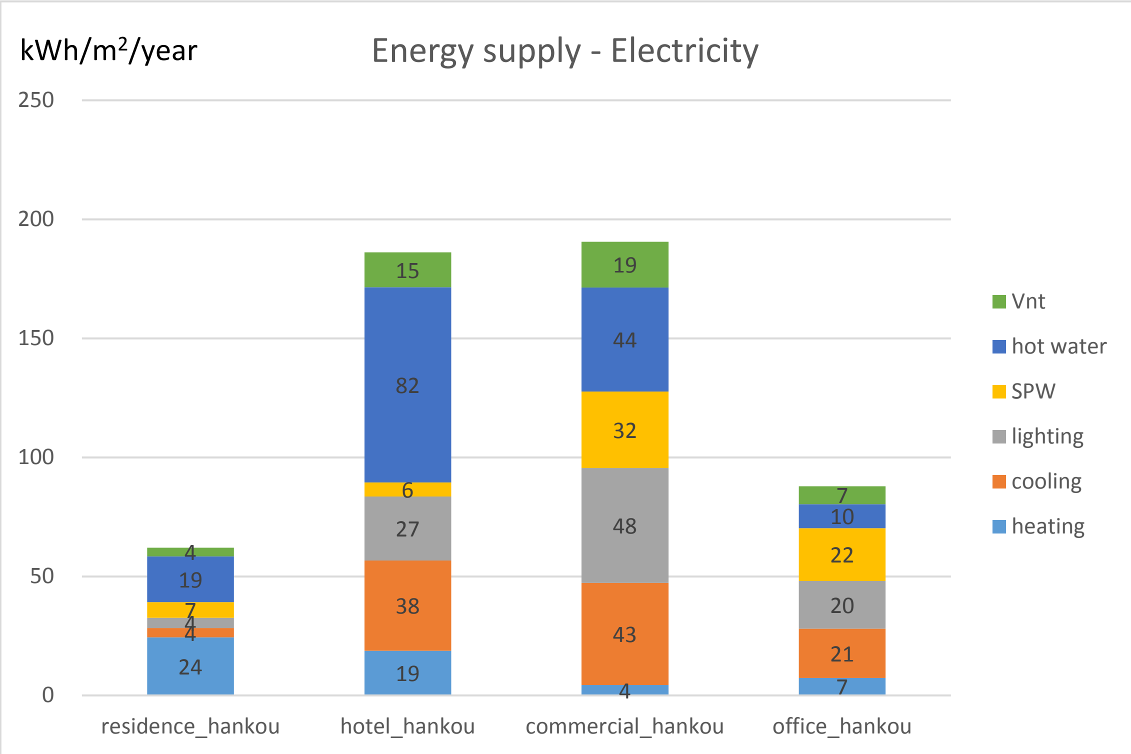


Figure 5.20 Annual energy supply per square metre by electricity

Table 5.13 Summary of the overall electricity supply in each building type

Building type	Electricity supply (kWh/ m^2/ year)						
	Vent	hot water	small power	lighting	cooling	heating	Total
Residential	4	19	7	4	4	24	**62**
Commercial	19	44	32	48	43	4	**186**
Office	7	10	22	20	21	7	**88**
Hotel	15	82	6	27	38	19	**191**

Figure 5.21 and Table 5.14 present the gas supply among these building types. Figure 5.21 shows that commercial buildings have the largest gas supply with 62 kWh/ m^2/ year in hot water compared to 8 kWh/ m^2/ year in residential buildings and 6 kWh/ m^2/ year in office buildings. Hotel buildings do not adopt gas for hot water use. Meanwhile, none of the four building types uses gas for heating purpose.

Table 5.14 Gas ratio and efficiency setting for four building types in heating and hot water（gas supply ）

		Heating	Hot water
Residence_hankou	Gas ratio	0	0.3
	System Efficiency	0.84	0.85
Commercial_hankou	Gas ratio	0	0.6
	System Efficiency	0.84	0.85
Office_hankou	Gas ratio	0	0.4
	System Efficiency	0.84	0.85
Hotel_hankou	Gas ratio	0	0.00
	System Efficiency	0.84	0.85

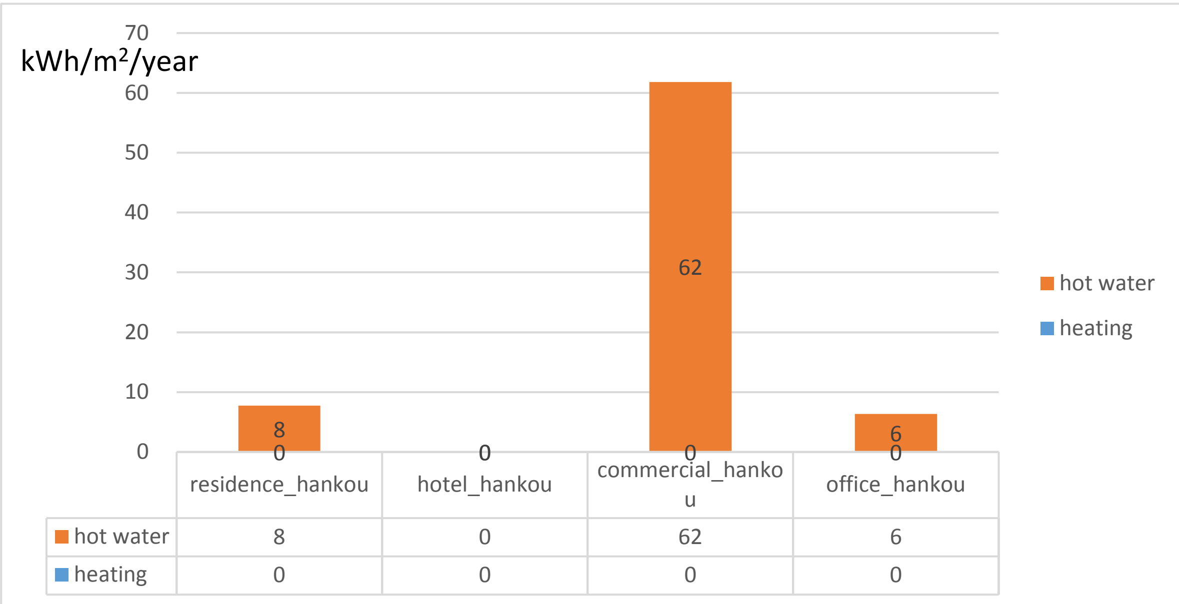


Figure 5.21 Annual energy supply per square metre by gas

Finally, carbon dioxide emissions are predicted in Table 5.15 based on the emission factors and internal loss ratio by transport and distribution.

Table 5.15 Annual operational carbon dioxide emissions from buildings

Operating carbon		**Electricity**	**Gas**	**Total**
Internal loss ratio (through transport and distribution)		**0.07**	**0.07**	
Carbon dioxide emission factor	tCO_2/MWh	**0.92**	**0.20**	
Carbon dioxide emission	tCO_2/a	**10440** Description: (net electricity supply(kWh/a)/1000)/ (1-0.07) *0.97	**521** Description: (gas supply(kWh/a)/1000)/ (1-0.07) *0.20	10961
	$kgCO_2/m^2/a$	64	3	67

Notes: carbon dioxide emission factors (0.92) is based on the reference: NDRC (National Development and Reform Commission) 2016.

5.2.6 Measurement vs simulation

The electricity demand for 14 buildings around Hankou railway station were measured from the Power Supply Company in two different places. One area for providing electricity consumption of public buildings is on Xinhua Road, and the location of the source of electricity provision for residential buildings is on Changqing Road. The electricity consumption was recorded from January 2015 to April 2016. The following three tables (Table 5.16 to Table 5.18) present the results of electricity consumption as well as the gas demand.

Table 5.16 The real electricity consumption from public buildings

Source: Data provided by Xinhua Power Supply Business Office

Year	Month	Electricity demands from Public buildings(kWh)		
		Wuhan Building of Science and Technology (office)	Wuhan Education Bureau (office)	Jiangfeng Building (commerce)
2015	Jan.	122400	148950	371880
	Feb.	157584	111006	314280
	Mar.	132816	103554	291120
	Apr.	68688	87534	334920
	May	57048	80478	350280
	Jun.	82056	124902	402840
	Jul.	118776	164106	528960
	Aug.	145680	128358	651720
	Sep.	111216	206445	555840
	Oct.	44736	95025	331800
	Nov.	40944	81009	311880
	Dec.	57168	88113	304080
2016	Jan.	57168	242736	309840
	Feb.	217752	170274	284760
	Mar.	109416	116700	254400
	Apr.	98952	91953	283800
Cumulative values		1622400	2041143	5882400

Table 5.17 The real electricity consumption from Donghang community

Source: Data provided by Changqing Power Supply Business Office

Year	Month	Electricity demands from Donghang Community（kWh）
2015	Jan.	65120
	Feb.	64328
	Mar.	51088
	Apr.	41188
	May	31456
	Jun.	44800

	Jul.	53200
	Aug.	86660
	Sep.	59224
	Oct.	32188
	Nov.	37548
	Dec.	59036
2016	Jan.	76324
	Feb.	86988
	Mar.	40652
	Apr.	37292
Cumulative values		867092

Table 5.18 The real electricity consumption from Hejiadun community

Source: Data provided by Changqing Power Supply Business Office

Year	Month	Electricity demands from Hejiadun community（kWh）
2015	Jan.	133415
	Feb.	103873
	Mar.	151990
	Apr.	94902
	May	83926
	Jun.	95230
	Jul.	140984
	Aug.	184912
	Sep.	139876
	Oct.	81122
	Nov.	92462
	Dec.	130214
2016	Jan.	152999
	Feb.	113640
	Mar.	116538
	Apr.	101875
Cumulative values		1917958

Table 5.16 to Table 5.18 show the real electricity consumption of the fourteen buildings from the January of 2015 to the April of 2016 provided by the Changqing and Xinhua Power Supply Business Office. The disadvantage is that it is impossible for these data to distinguish the electricity consumption in each component (such as the energy

consumption on hot water, heating, cooling, lighting), as well as individual's building energy consumption, because the power company only provides the energy consumption for the building cluster as a whole. The measured result is smaller than the simulated, and this was expected. Several reasons can explain this discrepancy. Firstly, the operational schedule from the local standards in the simulation is longer than the real working conditions. Based on the standards, the heating periods started from 8th November to 4th March of the following year, and 6th May to 8th September for cooling. Many locals even started to cool in July when it began extreme hot. In that case, more energy is calculated than the real situation. Therefore, higher energy consumption is bound to be calculated than the actual situation. Secondly, the occupant rate from buildings is not used at 100% for actual situations. According to the survey, for residential buildings, the occupant rate is around 96%, while for public buildings, this figure is even less. Taking Wuhan Building of Science and Technology as an example, there were refurbishment works taking place in the first five storeys. Moreover, some of the floors were unoccupied or utilised for other reasons such as business purposes. Finally, according to the local weather conditions, the monthly average humid is ranged from 70% to 80%, and this means the dehumidification is considered in the simulation. Therefore, the sensible and latent heat gains from buildings are all considered in the simulation, and this can also lead to a higher value than measurement.

However, due to difficulties in data collection of gas supply, the gas data in the urban area is from Wuhan Statistical Yearbook-2016 (Wuhan Bureau of Statistics 2017, P_{150}) as the benchmark. For example, for residential buildings in Jianghan district, according to the Yearbook, the average of annual household gas consumption is 154.17 m^3/ household/ year. In order to compare with the power consumption, the gas consumption is converted to the unit kWh/m^2/year. Taking the gas consumption of residential buildings in Case 1 for example, the result is 1716 kWh/ household /year (Conversion reference: https://www.businessenergy.com/gas/kwh-calculator.html), and 15 kWh/m^2/year based on the average residential floor area per household in Wuhan was 113.4 m^2 (Ye and Li 2012). For gas supply in public buildings, for example, no gas was used in hotel buildings, and this is based on the measurement. Table 5.19 calculates and summaries the annual energy demand for residential and public buildings from the measurements.

Table 5.19 Energy demand in the study area from the measurement

Building types	Floor areas（㎡）	The net area used by electricity（㎡）	Electricity demand(kWh/year)	Electricity demand (kWh/ m^2/ year)	Gas demand (kWh/ m^2/ year)	Total (kWh/ m^2/ year)
Residential buildings	75075	30,030 (40% floor area)	2,088,788	70	15	**85**
Commercial	22187	19,968 (90% floor area)	4,411,800	221	76	**297**
Office	56938	24978 (45% floor area)	2,747,657	110	6	**116**
Hotel	4881	3905 (80 % floor area)	905,960	232	0	**232**

Table 5.20 and Figure 5.22 shows energy demands of measurements and simulations, respectively.

Table 5.20 The measurement and simulation of energy demand

Simulation	Floor area (m^2)	Annual energy demand (kWh/ m^2/ year)
Residential	76857	113
Commercial	23565	309
Office	58542	140
Hotel	4917	265
Measurement	Floor area (m^2)	Annual energy demand (kWh/ m^2/ year)
Residential	75075	85
Commercial	22187	297
Office	56938	116

Hotel	4881	232

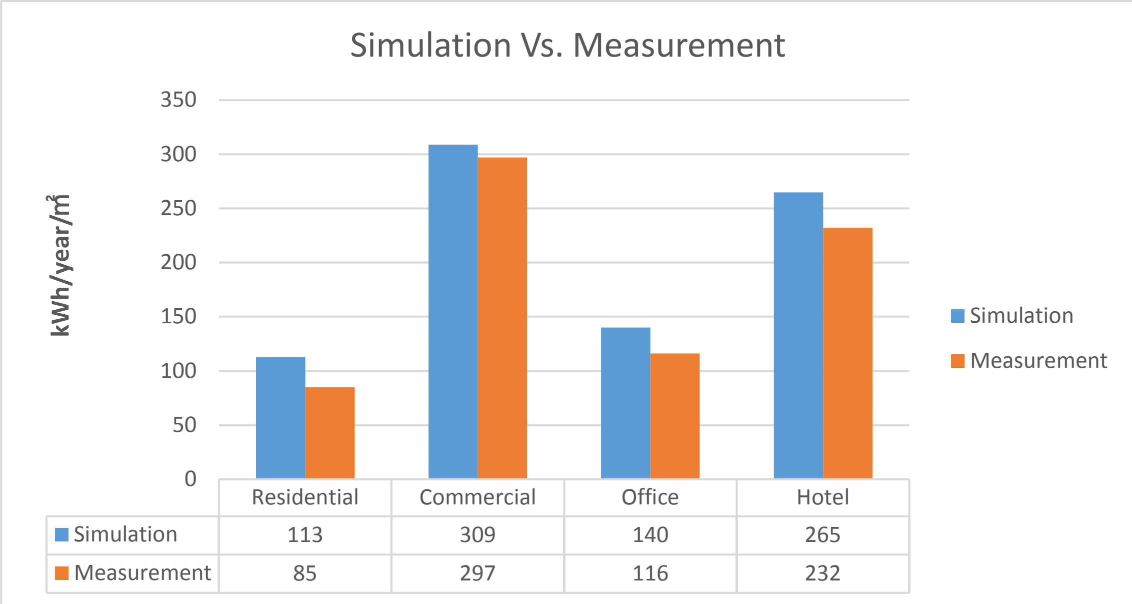


Figure 5.22 The energy demand of simulation vs measurement

As can be seen in Fig. 5.22, the simulation result is higher than the measurement. However, this result is accepted, with the error range of 4% to 38%. And this discrepancy agreed with researchers of Reinhart and Cerezo Davila (2016), which is from 12% to 55% for urban scale models. Furthermore, this value is agreed with the statistics from the Wuhan municipality level (**see Chapter 4 Fig. 4.8**). The largest discrepancy occurred in the residential buildings (38%) and office (20%), which is followed by the hotel and commercial buildings. All these discrepancies can be explained by unstable factors such as occupant behaviours, ventilation and incidental gains.

5.3 Case Study 2: Modelling building clusters around the Wuchang Station

5.3.1 Basic description in the study area

Fu jiapo Community around Wuchang Railway is in Wuchang District, downtown area. There are 536 households in the community, with a permanent population of around 1200 people (536*80%*3)—a total number of 20 residential groups. Figure 5.23 shows the study area (the red shaded area).

Figure 5.23 The red shaded area around Wuchang railway station is the study areas

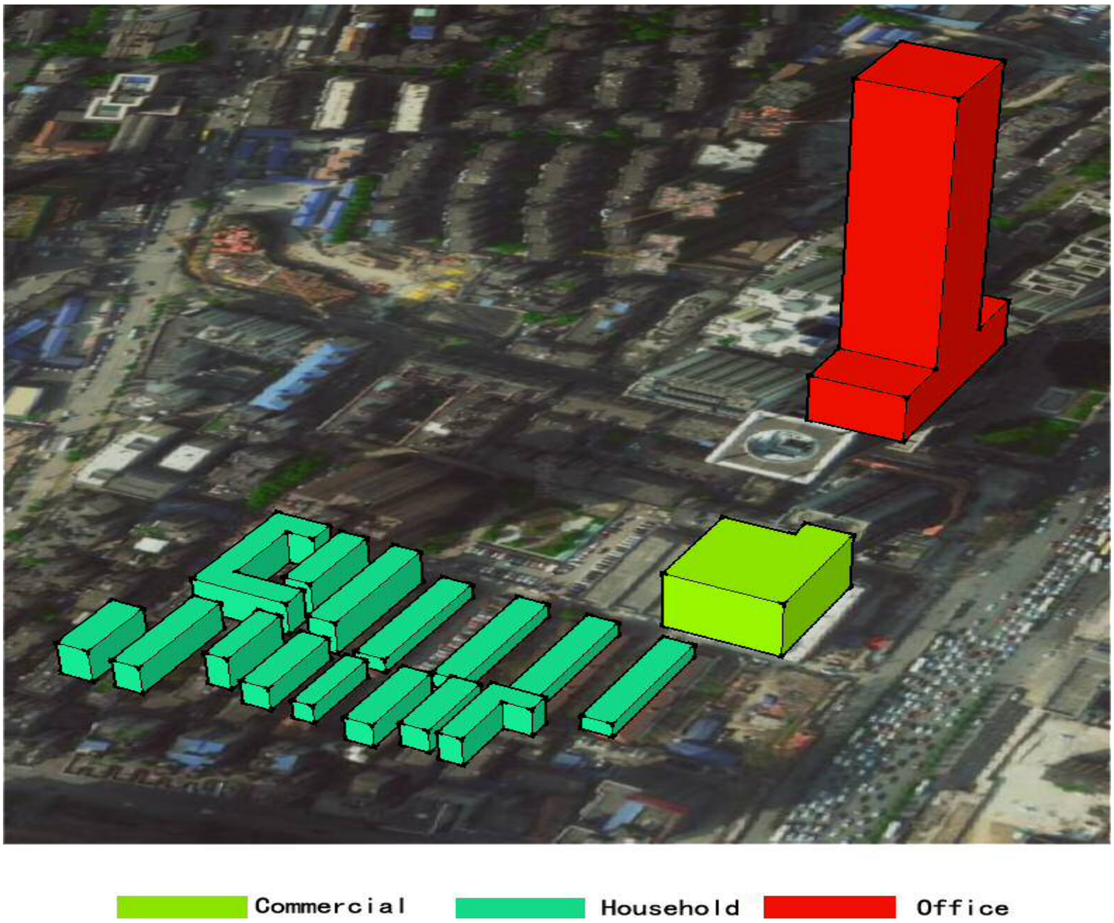


Figure 5.24 Building modelling in the study area

As for the study area shown in Fig. 5.24, this research selects seventeen buildings for modelling, which can be classified into three types —residential, commercial, and office buildings. As for the commercial buildings, the total floor area is around 16,000 square metres, with two underground storeys, and six above the ground with around 800 people. The office building shaded in red, called China Construction Third Engineering Bureau CO., LTD (CCTEB), is a 45-storey above the ground with around 1200 people. The other fifteen buildings are for residential use. The detailed information from the investigation is summarised in Table. 5.21:

Table 5.21 The statistics of the study area around Wuchang railway station …Source on-sit

Number	Building classification	Storey	Units	No. of households	No. of offices	No. of total buildings	Area (per floor) ㎡
1	Commercial	8					2674
2	Household	3	4	36		36	814
3		3	4	36		36	814
4		3	4	36		36	814
5		3	4	36		36	814
6		7	4	56		56	726
7		7	3	42		42	479
8		7	6	84		84	1197
9		6	2	24		24	495
10		5	2	20		20	432
11		5	2	20		20	479
12		4	2	16		16	322
13		5	2	20		20	479
14		7	2	28		28	349
15		6	2	24		24	632
16		7	2	28		28	492
17	Office	45					

5.3.2 Simulation conditions settings for building clusters around Wuchang Station

In the Case 2, most of the settings are the same as in Case 1. These settings include the meteorological conditions, internal heat gains, the rate of ventilation, and the operational schedule, but exclude building construction and materials. The building construction around Wuchang Railway Station has improved, especially in the U value of the external wall and the windows. Table 5.22 presents the real construction details of different building types from the investigation.

Table 5.22 The real construction information for different building types around Wuchang station

Building Types	Construction	U-Value（W/m²/℃）	Building Materials	Thickness（mm）
Residential Building	**Exterior Wall (From Outside to Inside)**	0.69	Cement Mortar	20
			B06 Aerated Concrete Block	200
			FH Inorganic Foam Insulation Board	30
			Cement Mortar	20
	Interior Wall	0.98	Cement Mortar	10
			B06 Aerated Concrete Block	200
			Cement Mortar	10
	Exterior Window (From Outside to Inside)	2.8	Glass	6
			Cavity (Argon)	9
			Glass	6
	Floor-Ceiling (From Top to Bottom)	1.67	Timber Floor	18
			Polyethylene Foam Plastic	2
			Core-Board	18
			Waterproof Layer	2
			Cement Mortar	20
			Ferro concrete	100
			Cement Mortar	20
	Ground	0.83	Cement Mortar	20

	(From Top to Bottom)		Expansion Vitrified Microsphere Heat Insulation Mortar	60
			C20 Fine Aggregate Concrete	100
			Compacted Clay	500
	Roof (From Top to Bottom)	0.5	Facing Brick	10
			Cement Mortar	25
			Waterproofing Materials Polyurethane	3
			Cement Mortar	20
			Hydrophobic Expanded Perlite Products	20
			Rock Wool Board	50
			Ferro concrete	120
			Lime and Cement Mortar	20

Building Types	Construction	U-Value（W/m²/℃）	Building Materials	Thickness（mm）
Public buildings including office and commercial buildings	Exterior Wall (From Outside to Inside)	0.69	Cement Mortar	20
			B06 Aerated Concrete Block	200
			FH Inorganic Foam Insulation Board	30
			Cement Mortar	20
	Interior Wall	0.98	Cement Mortar	10
			B06 Aerated Concrete Block	200
			Cement Mortar	10
	Exterior Window (From Outside to Inside)	2.8	Glass	6
			Cavity (Argon)	9
			Glass	6
	Floor-Ceiling (From Top to Bottom)	1.08	Cement Mortar	20
			Ferro concrete	120
			Expansion Vitrified Microsphere Heat Insulation Mortar	55
			Cement Mortar	20
	Ground (From Top to Bottom)	0.83	Cement Mortar	20
			Expansion Vitrified Microsphere Heat Insulation Mortar	60
			C20 Fine Aggregate Concrete	100
			Compacted Clay	500
	Roof (From Top to Bottom)	0.5	Facing Brick	10
			Cement Mortar	25
			Waterproofing Materials Polyurethane	3
			Cement Mortar	20
			Hydrophobic Expanded Perlite Products	20
			Rock Wool Board	50
			Ferro concrete	120
			Lime And Cement Mortar	20

5.3.3 Results description and analysis

Figure 5.25 and Figure 5.26 show the distribution of different gains in office buildings over twelve months. Firstly, the incidental and solar gains are the major and stable heat resources. Secondly, the ventilation gains fluctuate monthly. From September to June, ventilation gains make buildings lose heat; from June to September, they increase the total heat, which could increase cooling demand. Thirdly, fabric gains generally make buildings lose heat during most of the year. Finally, the figures show that the reduction of incidental gains and cooling demand would be an efficient way to save energy for office buildings.

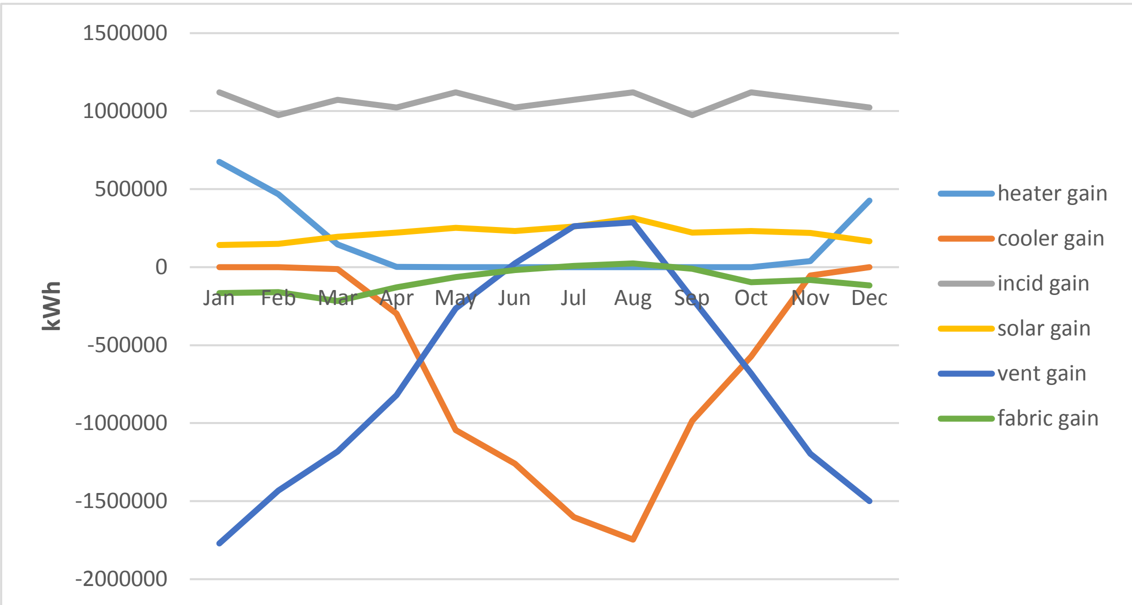


Figure 5.25 The monthly heat gains from the heater to fabric for office buildings

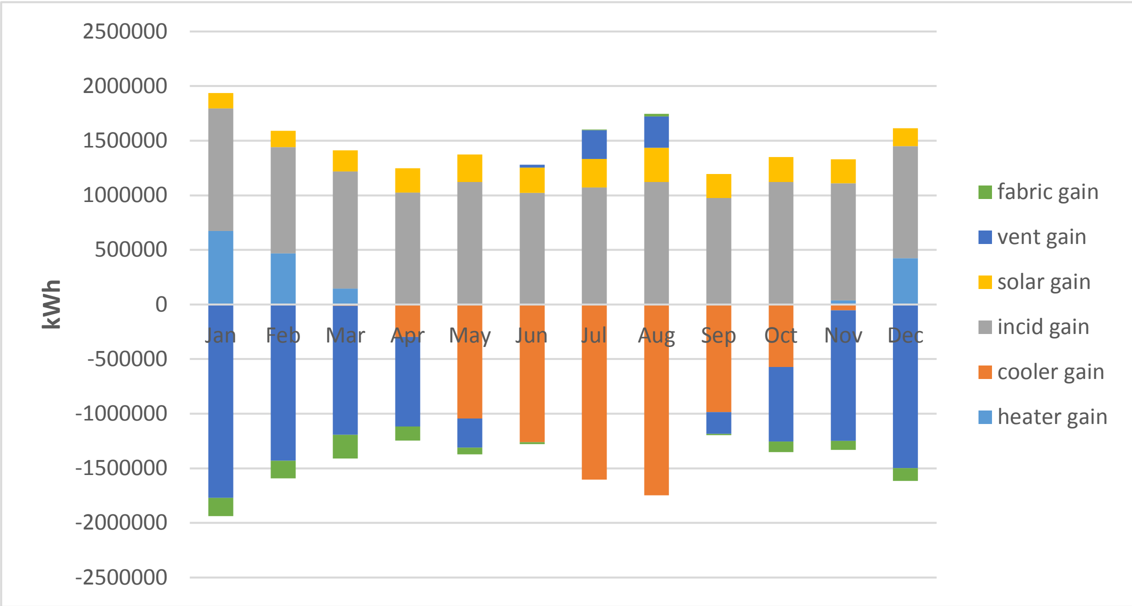


Figure 5.26 The distribution of monthly heat gains from fabric to heater for office buildings

The following two simulation results (Fig. 5.27 and Fig 5.28) describe the different heat gains distribution in commercial buildings. Firstly, incidental and solar gains are the major factors to heat buildings throughout the year. Moreover, the incidental gains are significantly greater than the solar gains. Secondly, the ventilation gains fluctuate. From September to June, buildings lose heat through ventilation, which could increase the heating demand. From June to September, they increase the heat in buildings, which could increase cooling demand. Thirdly, fabric gains usually make buildings lose heat during the year, but this loss is quite small. Finally, these two figures show that there is a significant cooling demand in July and August, but less heating demand in January and December compared to the cooling demand. In short, as these two figures indicate, for commercial buildings, reducing the incidental gains and cooling demand would be the biggest opportunity to save energy.

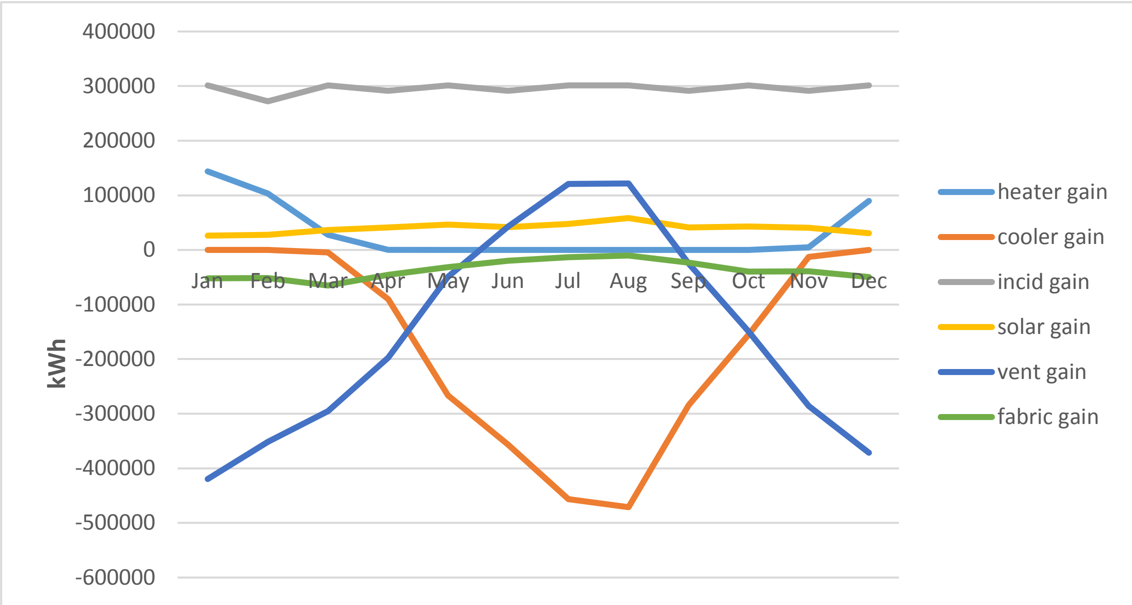


Figure 5.27 The monthly heat gains from the heater to fabric for commercial buildings

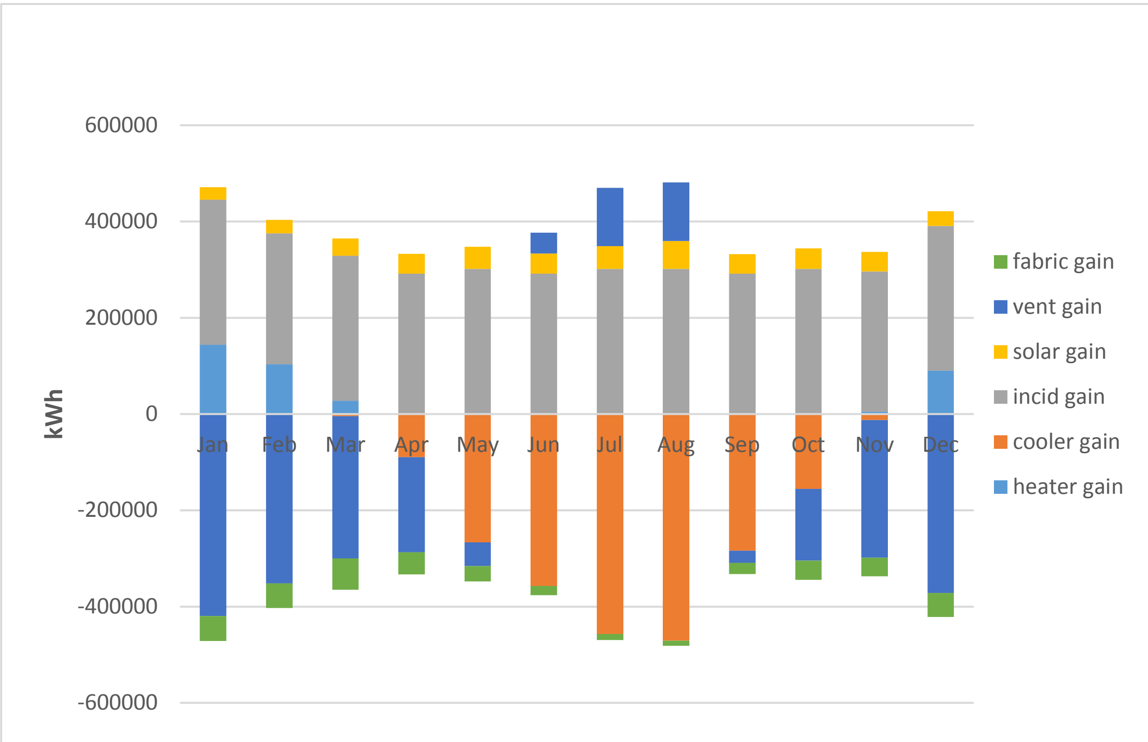


Figure 5.28 The distribution of monthly heat gains from fabric to the heater for commercial buildings

Figure 5.29 and Figure 5.30 show different heat gains in residential buildings. Firstly, incidental and solar gains are the two stable factors to heat buildings throughout the year. Secondly, the ventilation gains fluctuate. From September to June, they help buildings to release the heat accumulated from solar and incidental sources. From June to September, they increase the total heat, which could increase the cooling demand. Thirdly, fabric gains always make buildings lose heat throughout the year. Finally, the figures show that there is a large heating demand in winter periods. In addition, the peak heating demand is largely higher than the peak cooling demand, and this phenomenon is only observed in residential buildings.

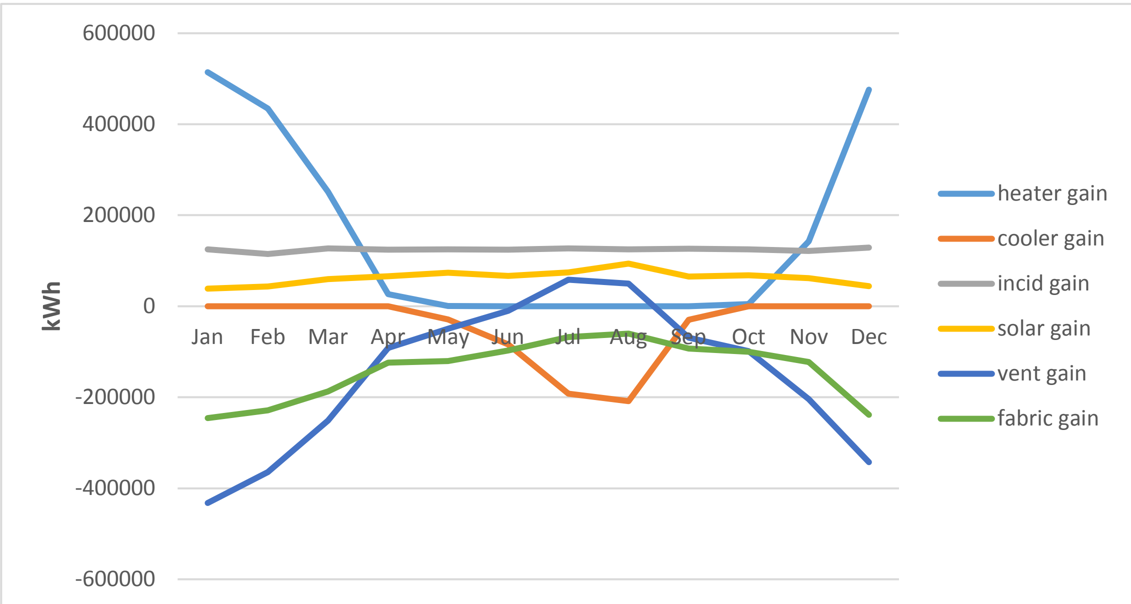


Figure 5.29 The monthly gains from the heater to fabric for residential buildings

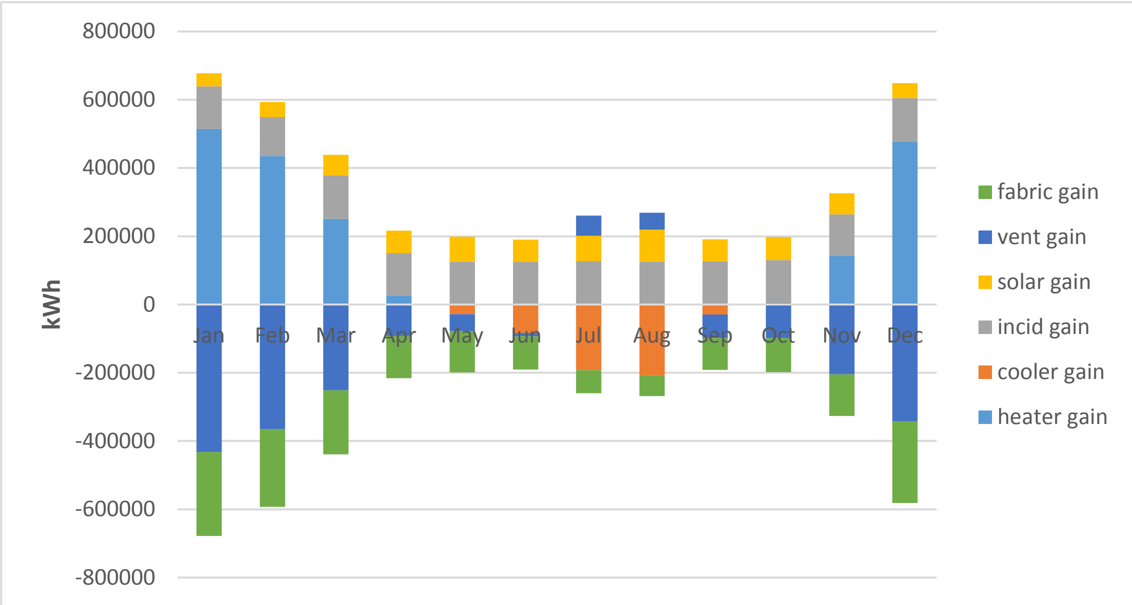


Figure 5.30 The distribution of monthly heat gains from fabric to the heater for residential buildings

From the simulation results for all buildings (Fig. 5.31 and Fig. 5.32), the incidental and solar gains are always the stable heat sources. In contrast, the ventilation and fabric gains vary considerably in their seasonal impacts, and this phenomenon is especially noticeable in the ventilation gains. Conversely, there is a significant cooling demand in the summer period, especially in July and August, and the peak cooling demand is markedly higher than the peak heating demand. Moreover, reducing incidental gains might be one way to save building energy.

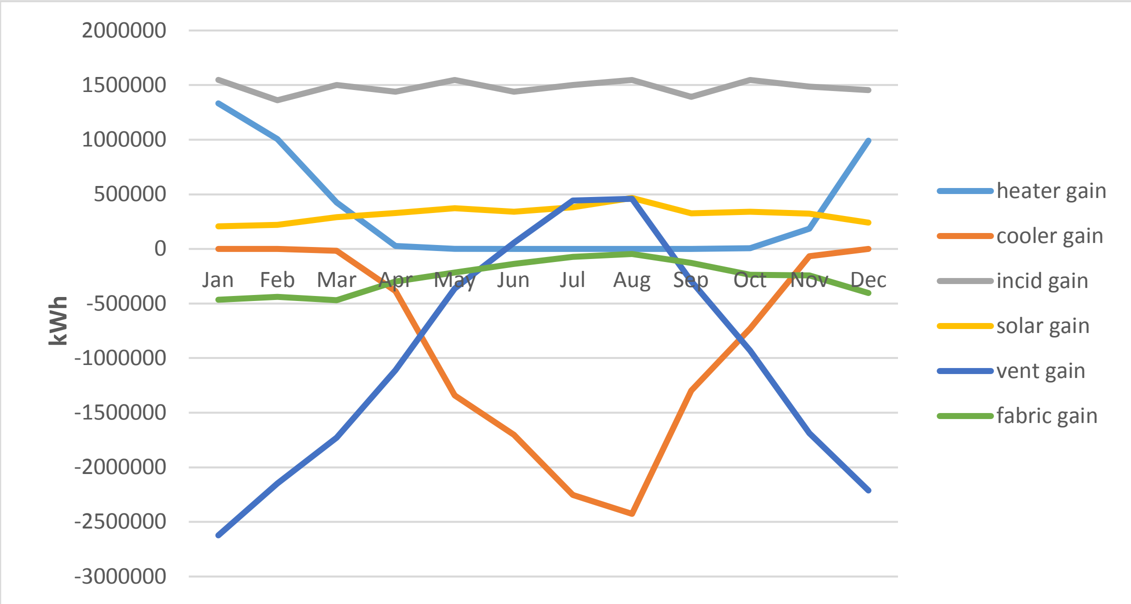


Figure 5.31 The monthly heat gain from the heater to fabric for all buildings

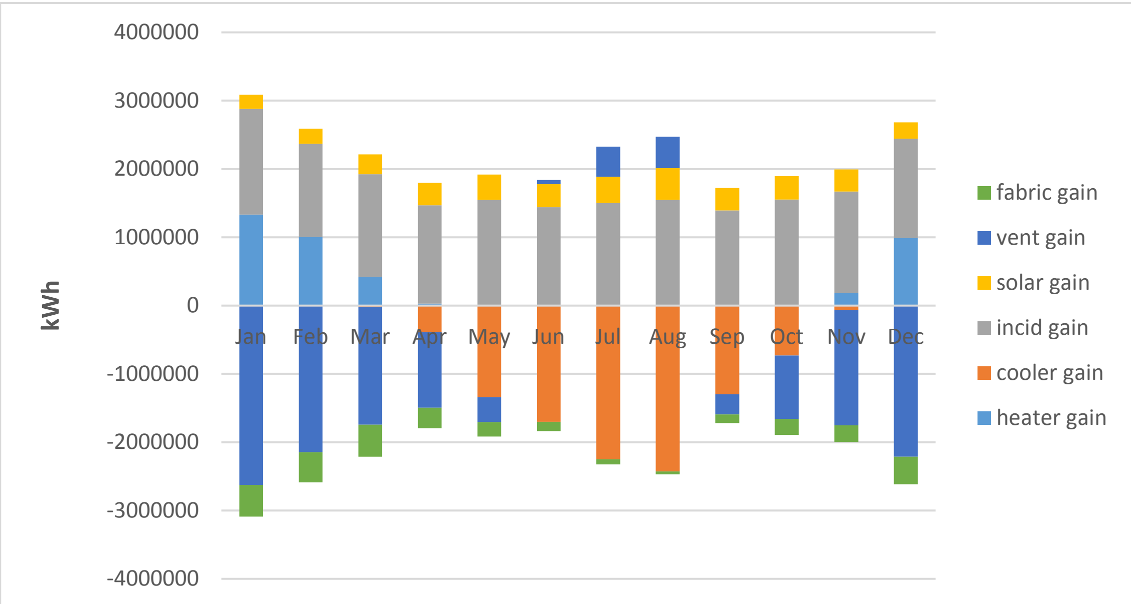


Figure 5.32 The distribution of monthly heat gains from fabric to heater for all buildings

Figure 5.33 shows the monthly cooling and heating demand. It is evident that the peak cooling demand is higher than the peak heating demand, with around 2.5 GWh/ month to 1.5 GWh/ month. The highest cooling demand occurred in July and August, while the greatest heating demand occurred in December and January.

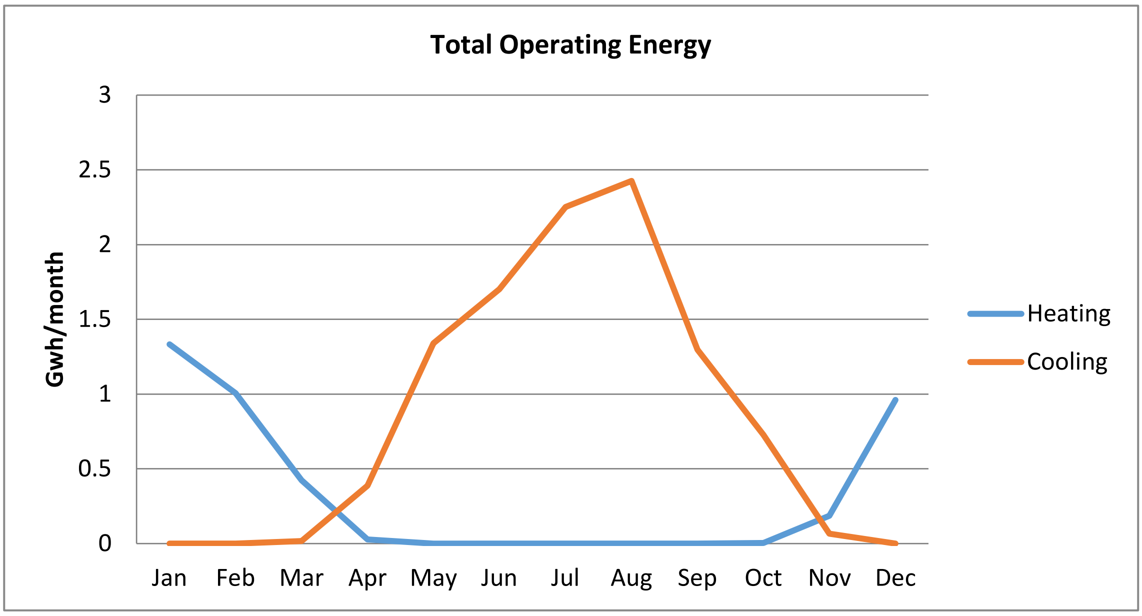


Figure 5.33 The monthly operational energy consumption for heating and cooling demand

Table 5.23 describes the heating and cooling demand among residential, office, and commercial buildings. There is the largest annual heating demand with 37 kWh/m^2/year in residential buildings, while the highest annual cooling demand with around 129 kWh/m^2/year in commercial buildings.

Table 5.23 Summary of annual heating and cooling demand from the simulation

Building types	Building floor area (m^2)	heating demand (kWh/year)	cooling demand (kWh/year)	heating demand (kWh/m^2/year)	cooling demand (kWh/m^2/year)
Residence_wuchang	48672	1,820,917	-542,634	37	-11
Office_wuchang	108274	1,753,544	-7,573,981	16	-70
Commercial_wuchang	16200	367,965	-2,106,399	23	-129

Figure 5.34 shows the annual energy demand distribution in heating, cooling, small power, lighting, and hot water among these three building types. Cooling demand was the largest energy consumption in commercial buildings, followed by hot water. This trend was also observed in office buildings. In contrast, for residential buildings, heating was the highest energy demand, followed by hot water. In short, as the bar graph

Figure 5.34 indicates, for commercial and office buildings, reducing the amount of cooling demand is the biggest opportunity for saving energy, while for residential buildings, the focus could be on a reduction in the heating demand.

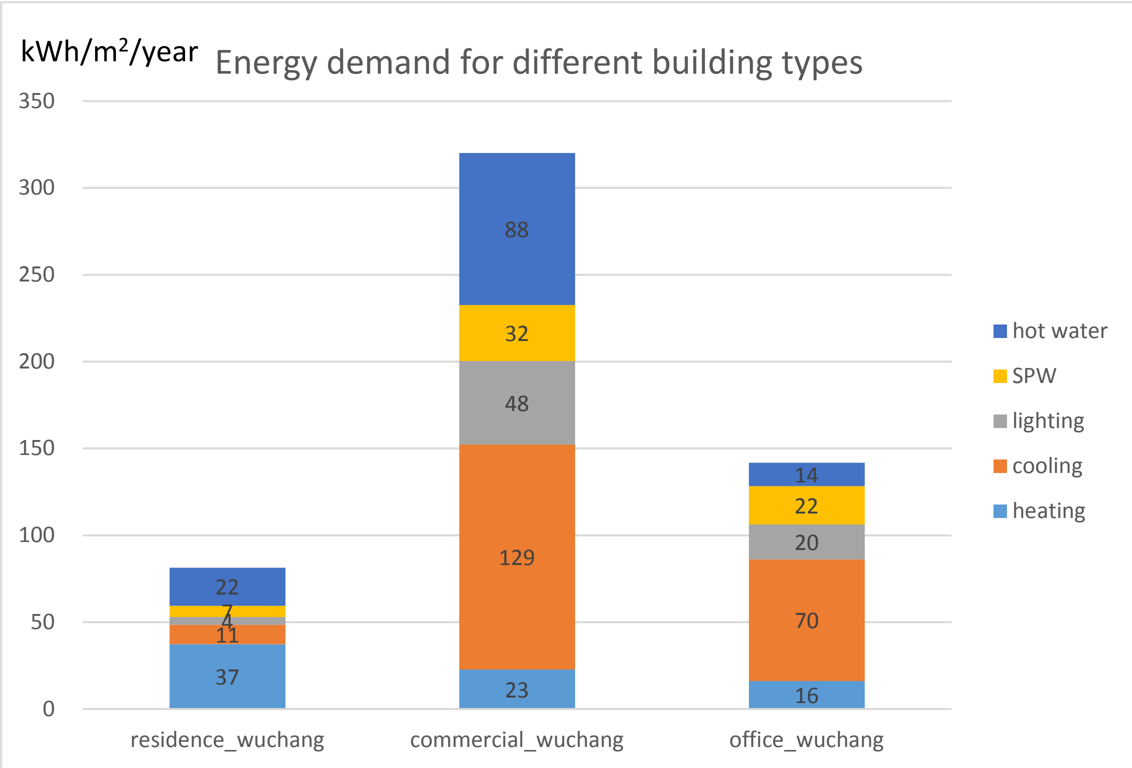


Figure 5.34 Annual energy demand for different building types per square metre

According to the power/gas ratio, and system efficiency, the energy supply can be predicted from the energy demand. This work uses the same condition as the previous case, which is the same power ratio and system efficiency (see Table 5.12) to calculate the electricity supply shown in Fig. 5.35 and gas supply are shown in Fig. 5.36.

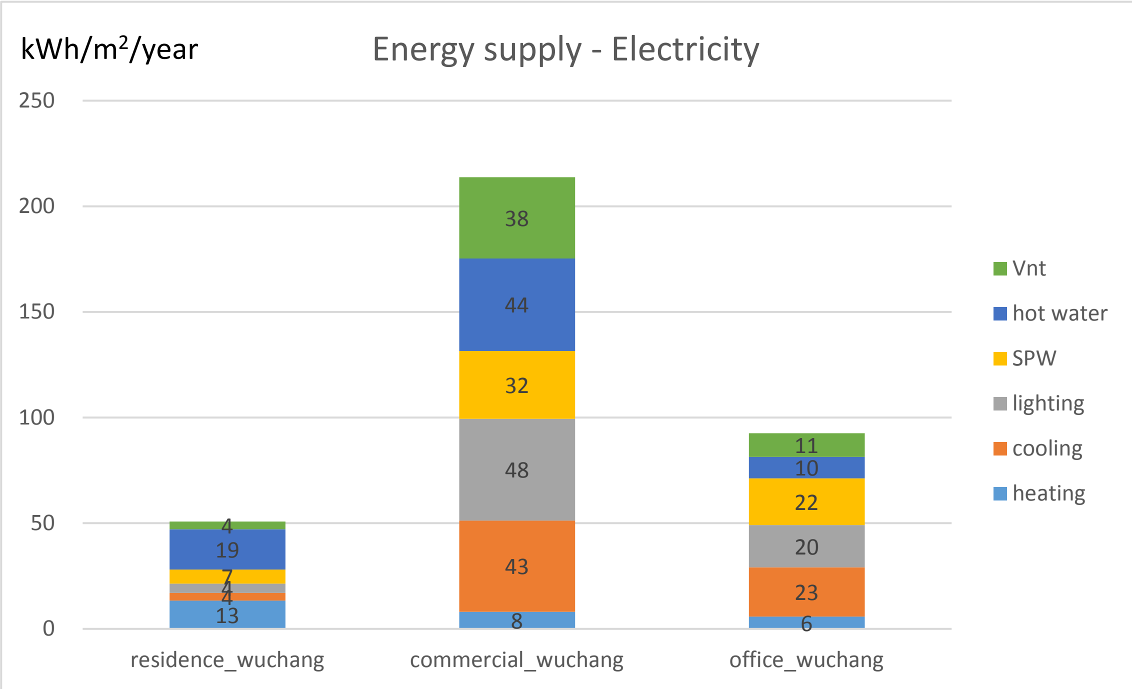
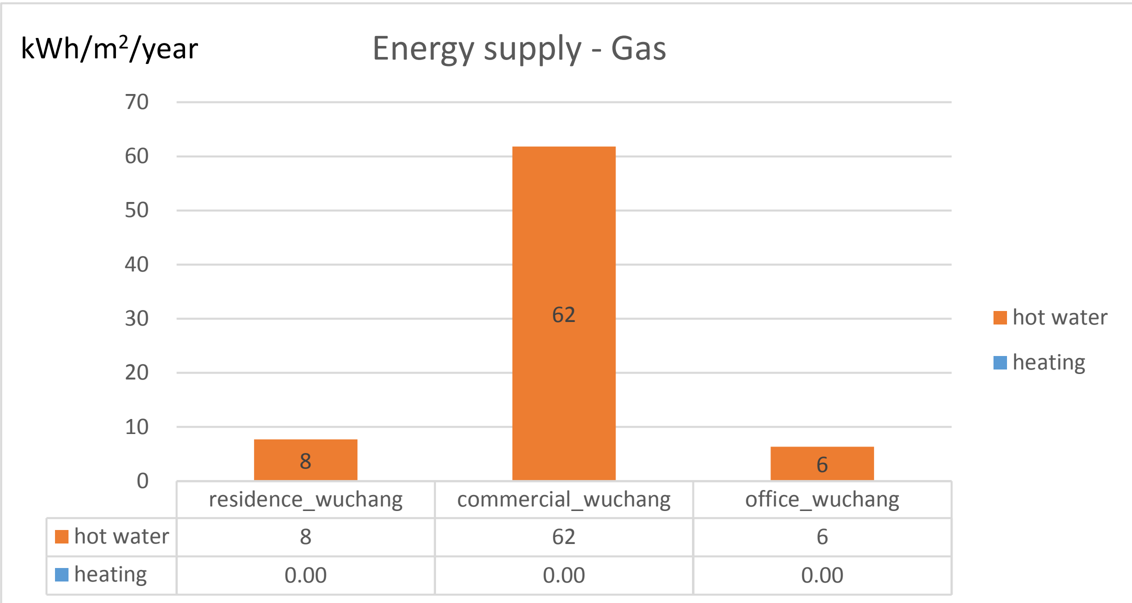


Figure 5.35 Annual energy supply per square metre by electricity



	residence_wuchang	commercial_wuchang	office_wuchang
hot water	8	62	6
heating	0.00	0.00	0.00

Figure 5.36 Annual energy supply per square metre by gas

As can be seen from the two figures above, commercial buildings need the largest power supply, followed by office and residential buildings. However, for the gas supply, commercial buildings still have the highest demand, followed by residential buildings and office buildings. Table 5.24 presents the results of the carbon dioxide emissions from all the buildings. The total annual carbon dioxide emissions from the buildings generated by electricity and gas are around 11,300 tonnes.

Table 5.24 Annual operational carbon dioxide emissions by electricity from buildings

Operating carbon		**Electricity**	**Gas**	**Total**
Internal loss ratio (through transport and distribution)		0.07	0.07	
Carbon dioxide emission factor	tCO_2/MWh	0.92	0.20	
Carbon dioxide emission	$kgCO_2/m^2/year$	60	3	63
	$tCO_2/year$	10355	444	10799

5.3.4 Measurement vs simulation

Table 5.25 to 5.27 present the data for the electricity consumption of the three building types covering around one year. The local power supply business centre provides these data.

Table 5.25 The real electricity consumption from residential buildings
Source: Data provided by the local Power supply business centre

Year	Month	Electricity demand from Fu Jiapo community（kWh）
2015	Feb.	93329
	Mar.	134147
	Apr.	90628
	May	87062
	Jun.	108970
	Jul.	160859
	Aug.	188840
	Sep.	126285
	Oct.	82140
	Nov.	74723

	Dec.	104156
Overall		1251139
2016	Jan.	141011
	Feb.	106418
	Mar.	91865
	Apr.	87574
	May	86948
Cumulative		1764955

Table 5.26 The real electricity consumption from office buildings

Year	Month	Electricity demand from China Construction Third Engineering Bureau CO., LTD（kWh）
2015	Apr.	503270
	May.	443042
	Jun.	666718
	Jul.	911306
	Aug.	882816
	Sep.	1023350
	Oct.	450242
	Nov.	392873
	Dec.	468024
Overall		5741642
2016	Jan.	966144
	Feb.	1250030
	Mar.	728434
	Apr.	615003
Cumulative		9,301,252

Table 5.27 The real electricity consumption from commercial buildings

Year	Month	Electricity demand from Langhui 68（kWh）
2015	Jun.	326393
	Jul.	352065
	Aug.	388480
	Sep.	364550
	Oct.	318332
	Nov.	278442
	Dec.	211533

Overall		2239795
2016	Jan.	230475
	Feb.	154067
	Mar.	272900
	Apr.	235559
	May	282947
	Jun.	314067
	Jul.	338973
Cumulative		4,068,783

Table 5.28 summarises the annual electricity and gas demand. It shows that commercial buildings have the largest energy consumption with 318 kWh/ m^2 / year, which is around 2.7 times that of office buildings and six times that of residential buildings. Table 5.29 presents the annual energy demand comparison between the simulation and measurement.

Table 5.28 Energy demand from the measurement in the study area

Building types	Floor areas （㎡）	Real air-conditioned area	Electricity demand (kWh/year)	Electricity demand (kWh/ m^2/year)	Gas demand (kWh/ m^2/year)	Total (kWh/ m^2/year)
Residential buildings	47,476	28,486 (60% floor area)	1,323,716	46	7	**53**
Commercial	16,042	14,438 (90% floor area)	3,487,528	242	76	**318**
Office	110,000	77,000 (70 % floor area)	8,585,771	112	8	**120**

Table 5.29 The measurement and simulation of energy demand

Simulation	Floor area (m^2)	Annual energy demand (kWh/ m^2/year)
Residential	48,672	81
Commercial	16,200	320
Office	108,274	142
Measurement	Floor area (m^2)	Annual energy demand (kWh/ m^2/year)
Residential	47,476	53
Commercial	16,042	318
Office	110,000	120

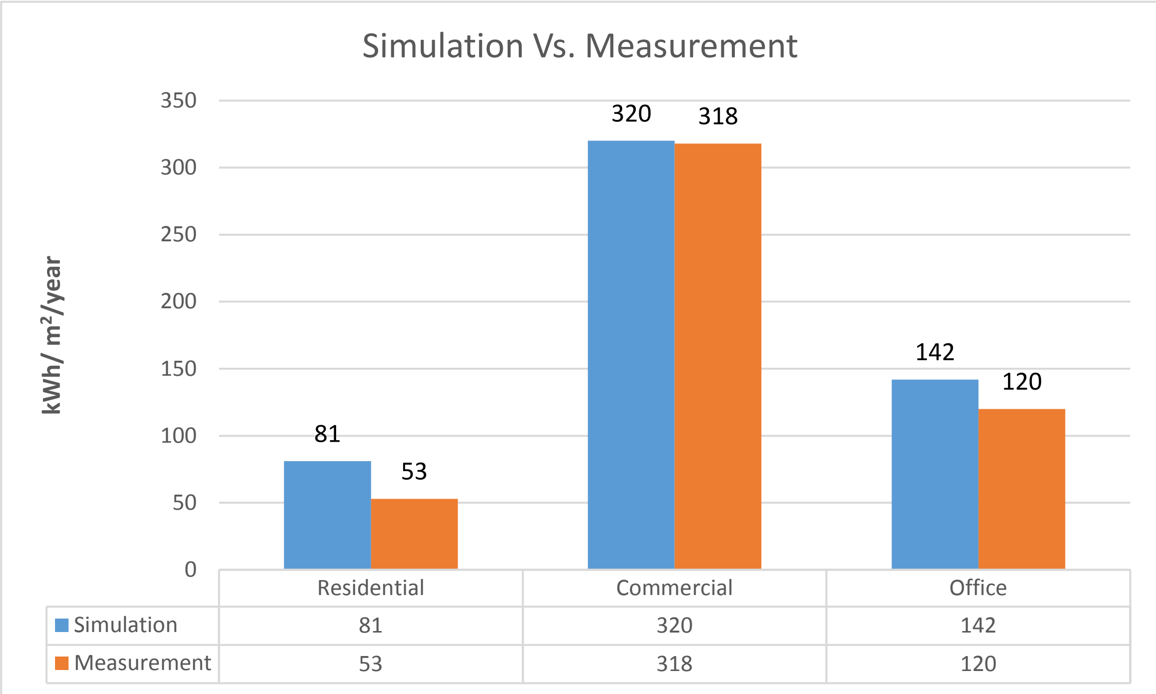


Figure 5.37 The energy demand for simulation vs measurement

As it can be seen in Fig. 5.37, the simulation result is larger than the measurement. For commercial buildings, there is almost the same between simulation and measurement, with 320 kWh/ $m^{2.}$ /year vs. 318 kWh/ m^2/year. However, for office buildings, the discrepancy is around 20 % between the simulation and measurement, and larger discrepancy in residential buildings as well.

5.4 Case Study 3: Modelling building cluster around the Wuhan Station

5.4.1 Basic description in the study area

In Case 3, this research works with the Ganghua community and Wushang Zhongyuan mall as the research objects (Fig. 5.38 and Fig. 5.39), which are around three to four kilometres from Wuhan station. There are around 760 households with 1830 people in the community. It was built in the year 2002 for dwelling use. Regarding the Wushang Zhongyuan mall that was completed in 2014, occupying with around 270,000 square metres, which includes 80,000 square metres for the underground use. The building is for mixed use, such as for shopping, recreation, and office, and has around 2,000 permanent people. Case 3 uses fifteen residential buildings to inform the Ganghua community (Fig. 5.38), and one commercial building represents public buildings (Fig. 5.39).

Figure 5.38 Residential buildings in Ganghua community

Figure 5.39 Public building of Wushang Zhongyuan mall for mixed use

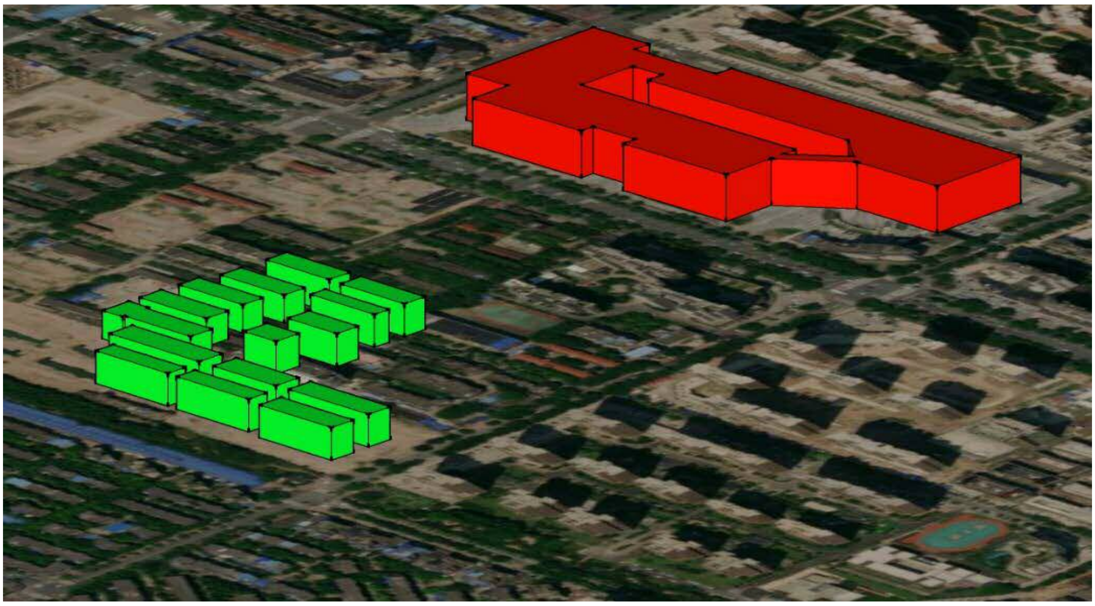


Figure 5.40 Images of the building modelling used in Case 3: domestic (green), commercial (red)

Figure 5.40 shows the models of the residential and public buildings in Case 3. Table 5.30 presents the basic information of the residential and commercial buildings in Case 3.

Table 5.30 The statistics of the study area around Wuhan station

Source: an on-site survey

Number	Building classification	Storey	Unit	No. of households	Area (per floor) ㎡	Area (total) ㎡
1	Households	7	4	56	798	5584
2		7	4	56	808	5653
3		6	5	60	808	4845
4		7	4	56	561	3925
5		6	4	48	778	4667
6		7	3	42	640	4483
7		6	4	48	888	5329
8		7	2	14	447	3131
9		6	5	60	1200	7201
10		7	5	70	1281	8966
11		7	4	56	888	6215
12		7	5	70	1072	7505
13		7	4	56	767	5371
14		7	5	70	801	5605
15		7	5	70	968	6776
16	Public (Wushang Zongyuan Mall)	Seven-storey（five above the ground and two under the ground)			270,000	270,000（above the ground:180,000 underground: 90,000)

5.4.2 Simulation conditions settings for building clusters around Wuhan Station

Basic simulation conditions in Case 3 is similar to the previous two cases. These conditions include weather file, internal heat gains and operational schedule. In this case, theoretically, there should be two HTB files: residential and commercial. In reality, according to the investigation, the public building is mostly for commercial use, but use the standards of residential building level. Therefore, only one HTB file is included in the Case 3 for the simulation. Moreover, the construction of the buildings, in this case, is quite like the Case 2 due to the time of construction and materials used in the buildings. As a result, the construction of residential buildings in Case 2 was also adopted in Case 3.

5.4.3 Results description and analysis

Figure 5.41 and Figure 5.42 show the distribution of different gains from commercial buildings. Firstly, incidental gains are the major and stable heat sources for buildings throughout the year, significantly greater than solar gains. Secondly, the ventilation gains fluctuate from the entire year. Thirdly, fabric gains always make building lose heat. Fourthly, the figures show that there is a significant requirement for cooling demand in July and August, as well as a greater heating demand in December and January.

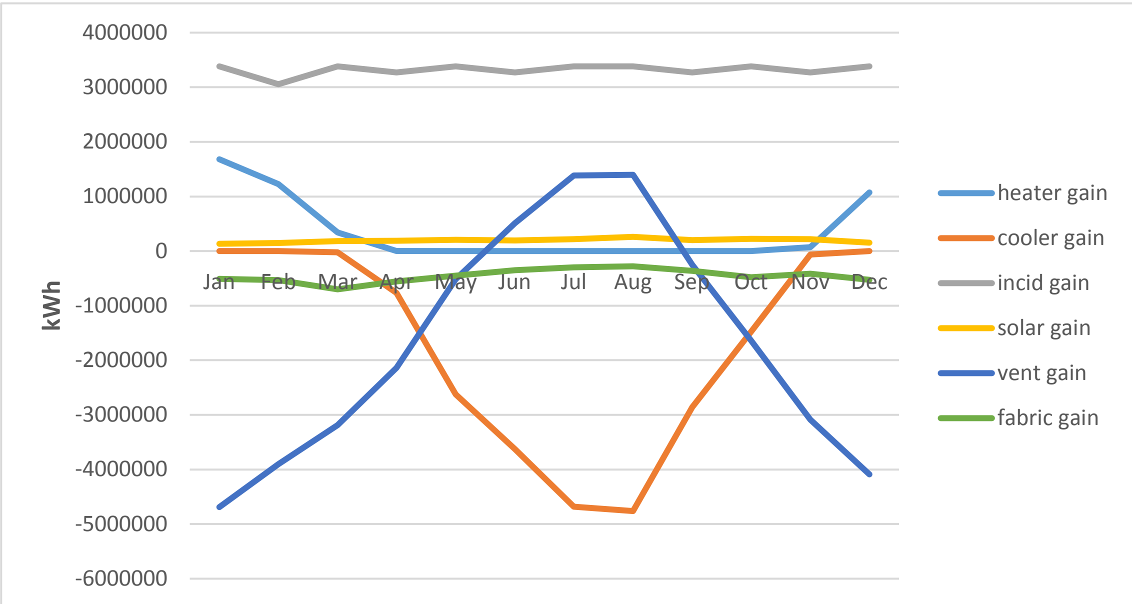


Figure 5.41 The monthly heat gains from the heater to fabric for commercial buildings

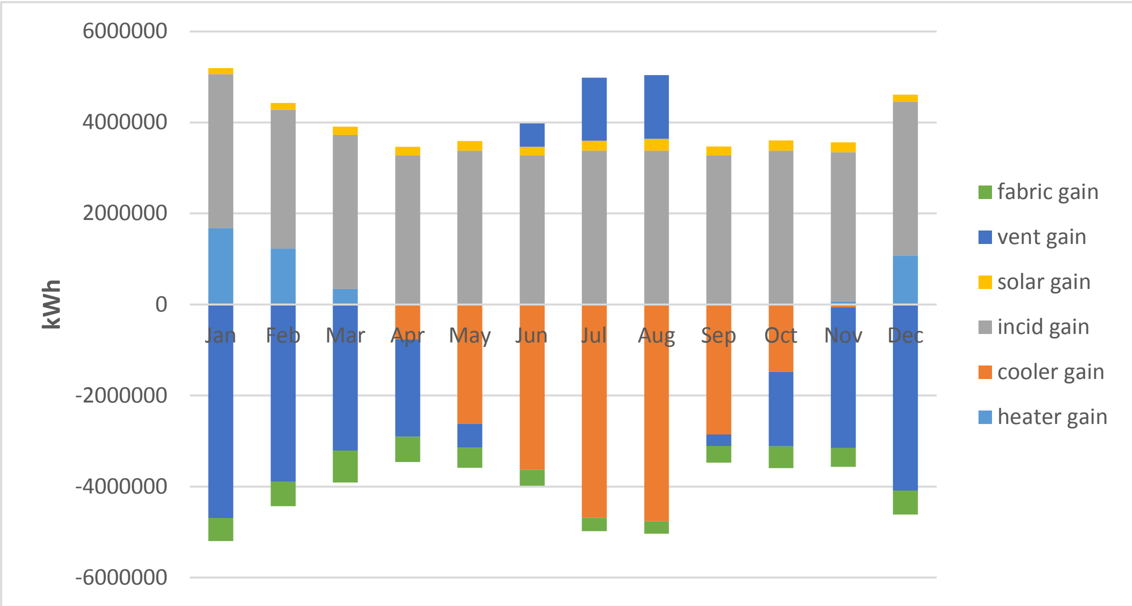


Figure 5.42 The distribution of monthly heat gains from fabric to the heater for commercial buildings

Figure 5.43 and Figure 5.44 illustrate different gains in all residential buildings throughout the year. Firstly, incidental and solar gains are two stable and significant factors. Secondly, ventilation gains fluctuate monthly. From September to June of the following year, ventilation gains help buildings to release the heat. In contrast, from June to September, they increase the total heat in buildings, which could increase cooling demand. Thirdly, fabric gains always contribute to a release of heat to the surrounding buildings. In short, the figures show that there is a significant requirement for cooling demand in summer and heating demand in winter. In addition, the peak heating demand is far greater than the peak cooling demand for residential buildings.

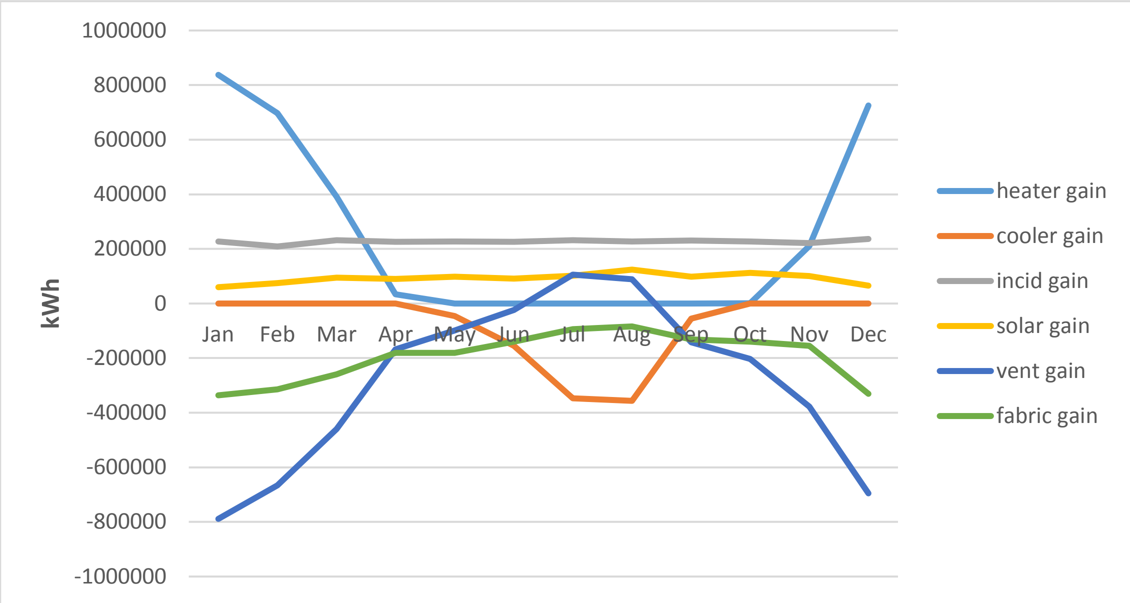


Figure 5.43 The monthly heat gains from the heater to fabric for residential buildings

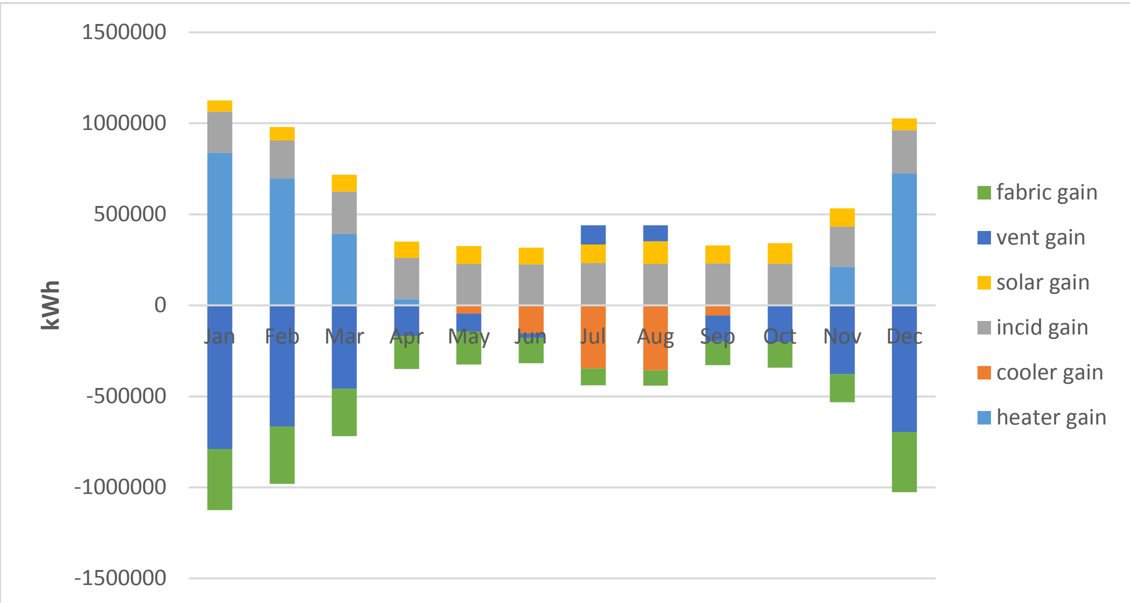


Figure 5.44 The distribution of monthly heat gains from fabric to the heater for residential buildings

The following two graphs (Fig. 5.45 and Fig. 5.46) illustrate the different gains for all buildings in the study area. Firstly, incidental and solar gains are the two stable factors. Secondly, the ventilation gains fluctuate throughout a year. Thirdly, fabric gains always make building lose heat during the year. In short, the figures show that there are huge potentials for saving energy through the reduction of incidental gains. More priorities should be given on the reduction of cooling demand from residential buildings and heating demand from commercial buildings.

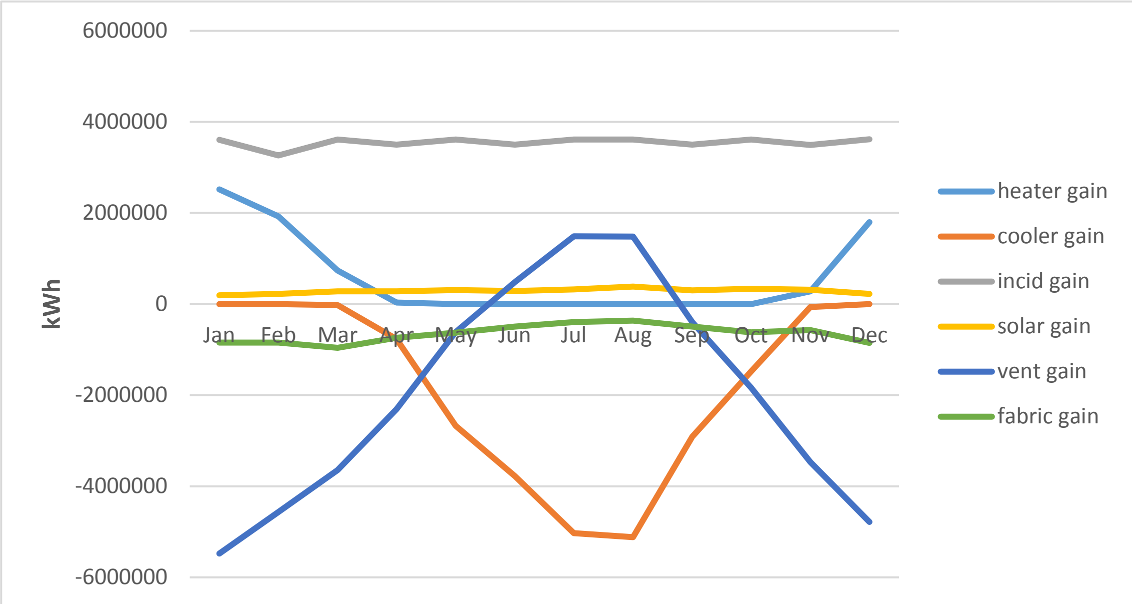


Figure 5.45 The monthly heat gains from the heater to fabric for all buildings

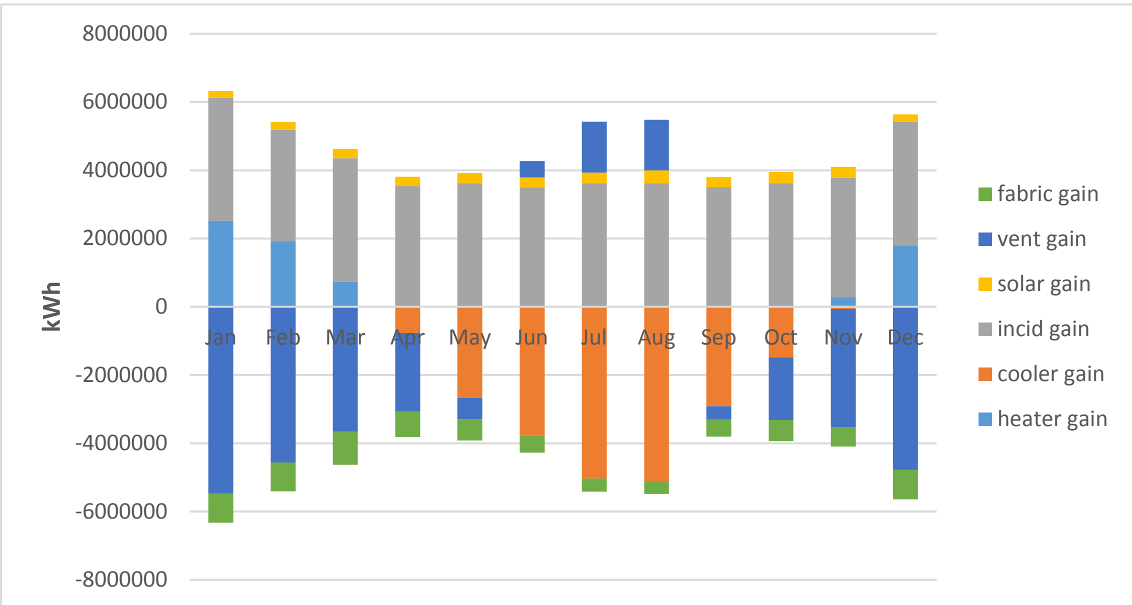


Figure 5.46 The distribution of monthly heat gains from fabric to heater for all buildings

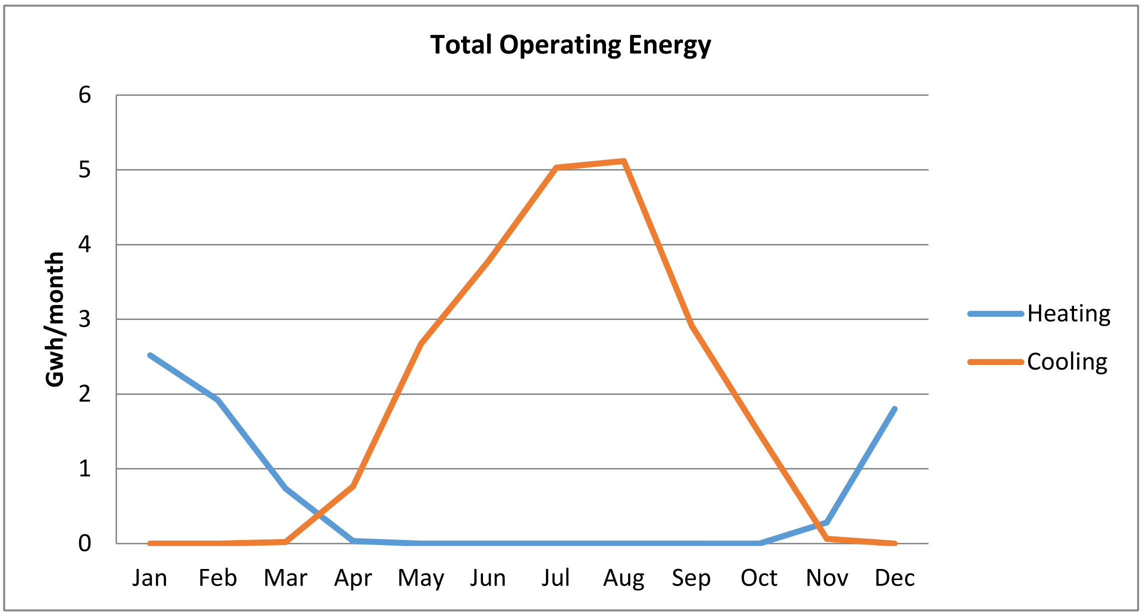


Figure 5.47 The monthly operational energy consumption for heating and cooling in residential and commercial buildings

Figure 5.47 and Table 5.33 present and compare the heating and cooling demand for the residential and commercial buildings. The cooling demand in commercial buildings is the largest, and far greater than the heating demand. Moreover, the heating demand in residential buildings needs more than cooling demand. In short, cooling is the largest energy demand in the commercial building, while heating is the primary energy consumption in residential buildings.

Table 5.31 Summary of annual heating and cooling demand from the simulation

Building type	Building floor area (m^2)	heating demand (kWh/year)	cooling demand (kWh/year)	heating demand (kWh/ m^2/year)	cooling demand kWh/ m^2/year)
Residence_wuhan	88,579	2,894,481	-963,347	33	-11
Commercial_wuhan	181,873	4,395,552	20,905,934	24	-115

Figure 5.48 is the total energy demand for residential and commercial buildings. It can be seen clearly that the energy demand in commercial buildings is almost four times larger than that of residential buildings. The cooling demand is, in fact, the largest in

commercial buildings, while heating demand is the largest among the residential buildings.

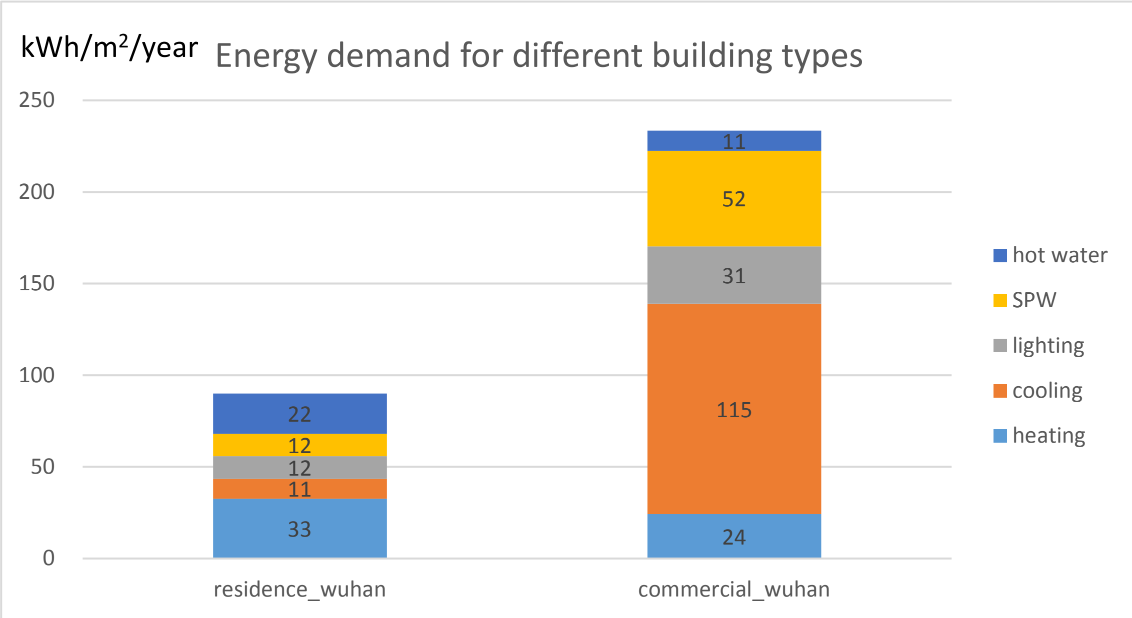


Figure 5.48 Annual energy demand per square metre for different building types

Figure 5.49 and Figure 5.50 present the annual energy supply by electricity and gas for the residential and commercial buildings. The electricity supply is far greater than the gas supply. From these two building types, the energy supply by electricity and gas in commercial buildings is greater than residential buildings. Moreover, gas is not used as an energy source for the heating of both building types.

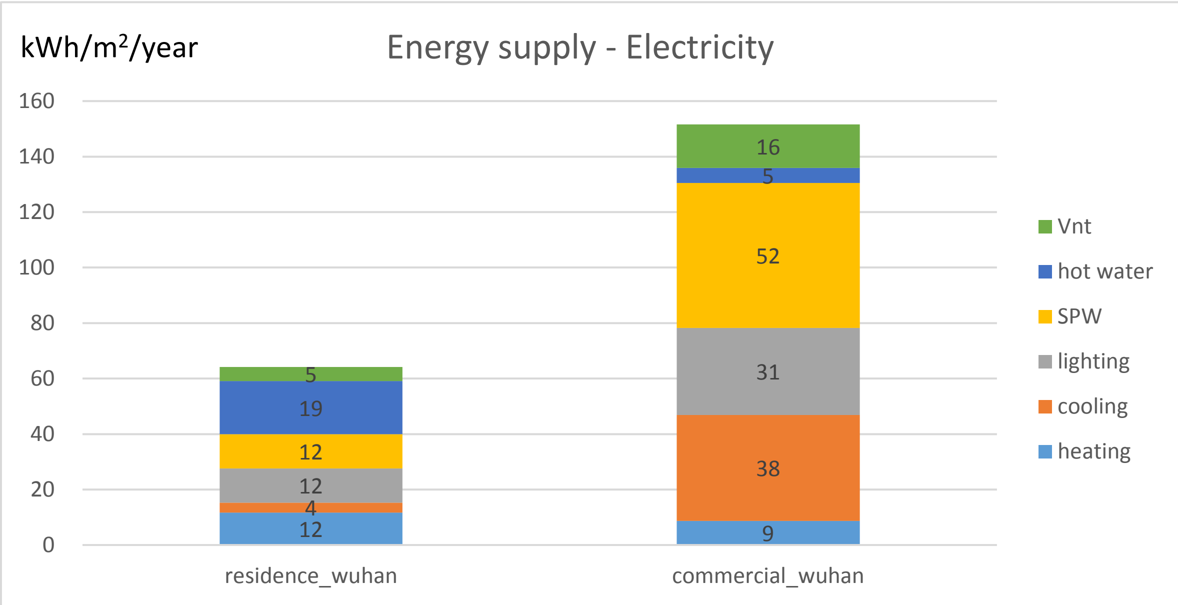


Figure 5.49 Annual energy supply per square metre by electricity

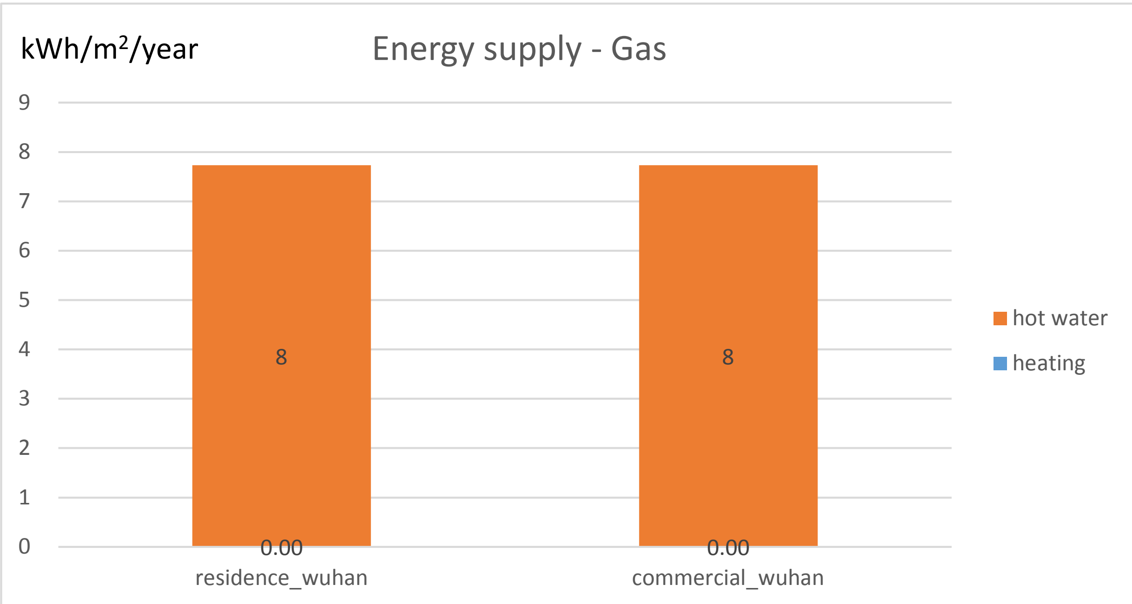


Figure 5.50 Annual energy supply per square metre by gas

Table 5.32 describes the results of the annual carbon dioxide emissions from the two building types. The annual carbon dioxide emissions generated by electricity and gas from commercial buildings are far more than those generated by residential buildings, especially for electricity. Moreover, carbon dioxide emissions measured in the unit of $kgCO_2/m^2$/year from Case 3 are far greater than the previous two cases, and this would be explained by the large floor area of commercial buildings in case 3.

Table 5.32 Annual operational carbon dioxide emissions from buildings

Operating carbon		**Electricity**	**Gas**	**Total**
Internal loss ratio (through transport and distribution)		0.07	0.07	
Carbon dioxide emission factor	tCO_2/MWh	0.92	0.20	
Carbon dioxide emission	$kgCO_2/m^2$/year	87	2	89
	tCO_2/year	23398	450	23847

5.4.4 Measurement vs simulation

Table 5.33 and Table 5.34 describes the monthly electricity consumption from residential and commercial buildings from power supply business office.

Table 5.33 The real electricity consumption from Ganghua residential community
Source: Data provided by Gangdong Power Supply Business Office

Year	Month	Electricity demand from Ganghua Community（kWh）
2015	Jun.	93001
	Jul.	127118
	Aug.	259139
	Sep.	131403
	Oct.	84455
	Nov.	85550
	Dec.	118265
Overall		898931
2016	Jan.	139317

	Feb.	114090
	Mar.	123950
	Apr.	92384
	May	81869
	Jun.	85143
Cumulative		1,535,684

Table 5.34 The real electricity consumption from Wushang Zhongyuan mall

Source: Data provided by Gangcheng Power Supply Business Office

Year	Month	Electricity demands from Wushang Zhongyuan Mall (kWh)
2015	Jun.	4406299
	Jul.	4752879
	Aug.	5244481
	Sep.	4921421
	Oct.	4297488
	Nov.	3758968
	Dec.	2855701
Overall		30237237
2016	Jan.	3111412
	Feb.	2079902
	Mar.	3684147
	Apr.	3180051
	May	3819788
	Jun.	4239903
	Jul.	4576132
Cumulative values		54,928,572

Table 5.35 is the summary of the energy demand from these two building types. It can be seen that the annual electricity demand from the commercial building of Wushang Zhongyuan Mall is more than three times that of the demand from residential buildings

(210 kWh/ m^2/year vs 62 kWh/ m^2/year). Table 5.36 shows the comparison of annual energy demand of the measurement and simulation.

Table 5.35 The summary of energy demand from the measurement in the study area

Building types	Floor areas (㎡)	Real air-conditioned area (㎡)	Electricity demand(kWh/year)	Electricity demand (kWh/ m^2/year)	Gas demand (kWh/ m^2/year)	Energy demand (kWh/ m^2/year)
Residential buildings	85,256	25,313 (30% floor area)	1,417,554	56	6	**62**
Wushang Zhongyuan Mall	180,000	180,000 (100 % floor area on the ground)	31,428,633	174	36	**210**

Table 5.36 Measurement and simulation comparison

Simulation	Floor area (m^2)	Annual energy demand (kWh/m^2/ year)
Residential	88,579	90
Wushang Zhongyuan Mall	181,873	234
Measurement	Floor area (m^2)	Annual energy demand (kWh/m^2/ year)
Residential	85,256	62
Wushang Zhongyuan Mall	180,000	210

Figure 5.51 compares the results of the measurement and simulation. The simulation results are much higher than the measurements, and this is especially observed in the residential buildings. As for the commercial buildings, the discrepancy is much smaller. Reasons for these discrepancies could potentially be some unstable factors such as occupants' activities and heat gains in the buildings.

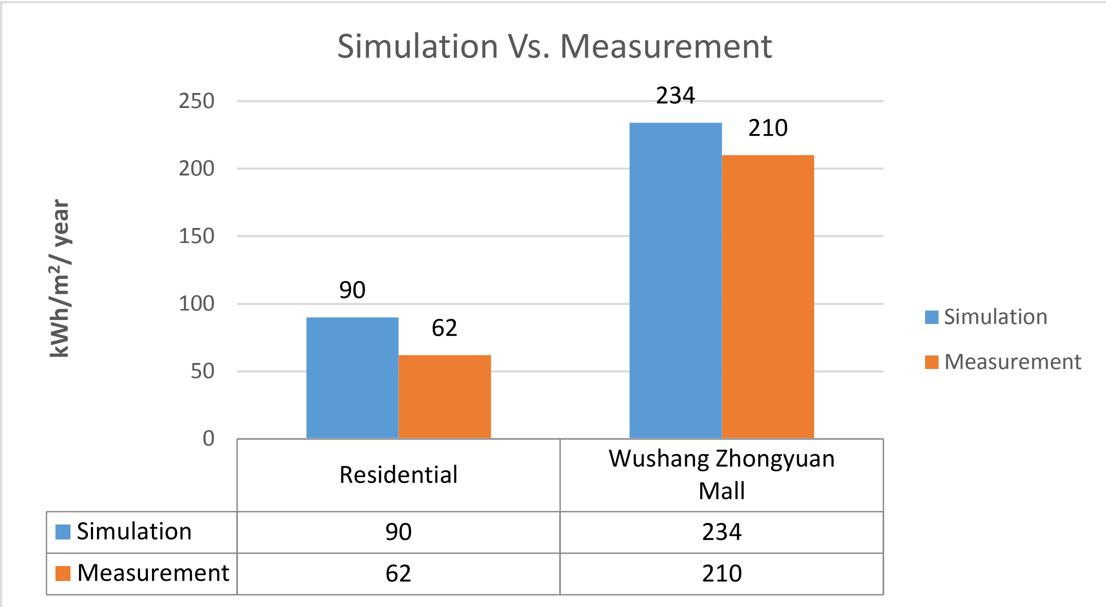


Figure 5.51 The energy demand for simulation vs measurement

5.5 Results comparison and conclusions

This chapter aims to understand the energy performance and carbon dioxide emissions of different buildings in three cases through the simulation and measurements. The results not only present the energy performance of various building types but also recognise the differences in energy consumption and distribution among different building types. Additionally, the simulation contributes to indicating several potential variables of energy demand on buildings and verify the accuracy of the simulation results through a comparison with the on-site measurements. The comparison and analysis of carbon dioxide emissions from these three cases are presented in Table 5.37:

Table 5.37 Carbon dioxide emissions comparison from buildings in the three cases

<table>
<tr><td rowspan="4">Hankou station</td><td rowspan="3">Residential
Floor area (m^2)</td><td colspan="4">Public buildings</td></tr>
<tr><td colspan="4">Floor area (m^2)</td></tr>
<tr><td>Commercial</td><td>Office</td><td>Hotel</td><td>Total</td></tr>
<tr><td>75,075</td><td>22,187</td><td>56,938</td><td>4881</td><td>84,006</td></tr>
<tr><td rowspan="2">Carbon dioxide emissions</td><td colspan="5">10961 t CO_2/ year</td></tr>
<tr><td colspan="5">67 kg CO_2/m^2/year</td></tr>
<tr><td rowspan="3">Wuchang station</td><td rowspan="2">Floor area (m^2)</td><td colspan="4">Floor area (m^2)</td></tr>
<tr><td>Commercial</td><td>Office</td><td colspan="2">Total</td></tr>
<tr><td>47,476</td><td>16,042</td><td>110,000</td><td colspan="2">126,042</td></tr>
<tr><td rowspan="2">Carbon dioxide emissions</td><td colspan="5">10799 t CO_2/ year</td></tr>
<tr><td colspan="5">63 kg CO_2/m^2/year</td></tr>
<tr><td rowspan="3">Wuhan Station</td><td>Floor area (m^2)</td><td colspan="4">Floor area (m^2)</td></tr>
<tr><td rowspan="2">85,256</td><td colspan="4">Commercial</td></tr>
<tr><td colspan="4">180,000</td></tr>
<tr><td rowspan="2">Carbon dioxide emissions</td><td colspan="5">23847 t CO_2/ year</td></tr>
<tr><td colspan="5">89 kg CO_2 /m^2/year</td></tr>
</table>

The table above compares carbon dioxide emissions from three cases. It shows that the annual per square metre carbon dioxide emissions around Wuhan station was the highest, standing at 89 kg CO_2 /m^2 /year, followed by Hankou and then Wuchang, respectively. Moreover, it can be concluded that the floor area of commercial buildings would have a significant impact on carbon dioxide emissions. More conclusions are presented as follows:

Energy performance characteristics of building clusters

(1) These building clusters can be classified into two types relating to non-domestic

and domestic building clusters. Office, commercial, and hotel buildings belong to the non-domestic category, and the rest of the building types belong to the domestic group. For the former, the cooling demand is the primary energy consumption and is at its highest demand from July to August. For the latter, the heating demand is the primary energy consumption, and this peaks in December and January.

(2) From these three cases, one common conclusion is that the floor area of commercial buildings has a significant impact on carbon dioxide emissions. More specifically, carbon dioxide emissions from Case 3 is around 30 % higher than the other two cases. One possible reason for this is that the floor area of the commercial building in the Case 3 is the highest compared with the other two cases.

(3) Monthly gains from incidental, solar, fabric and ventilation vary in buildings. The incidental gains overwhelm all other heat sources for all building types. Solar gains are the second greatest stable heat source. Gains associated with ventilation and fabric usually fluctuates during the year for all building types. Moreover, fabric gains help most of the buildings to release extra heat from the interior spaces to the outside. Reducing incidental gains might be the effective way to cut down energy use for buildings.

Validation of simulation results

Firstly, simulation conditions involved in the diary, building construction, and design conditions, could be defined based on national statistics, building codes, practical measurements, and design principles. Secondly, the simulation method is an effective way to get a better understanding of energy performance of building clusters with the minimum cost. In short, the simulation results and practical measurements not only revise the energy performance of building clusters but also show that the building energy modelling is highly reliable. On the other hand, the technical tool VirVil applied in this research is suitable because of the consideration of overshadowing between buildings. However, by comparing the simulation results of various building categories with the practical measurements, although the value of the simulation is larger than the measurement, the discrepancy can be recognised in an accepted range in all the cases, and this means that the tools can be validated as being reliable.

Chapter 6 Modelling Carbon Dioxide Emissions Due to Mobilities of Users from Buildings

6.1 Introduction

Chapter Six focuses on answering the following question:

"What models can be applied to predict transport-related carbon dioxide emissions from travel activities due to mobilities of users from buildings?"

To answer this questions above, this research applies activities-based transport demand model to predict the transport-related carbon dioxide emissions. The results are described and analysed, and then suggestions are proposed for the reduction of transport-related carbon dioxide emissions.

In this chapter, three representative areas of Case 1 (in the fringe district), Case 2 (inner city) and Case 3 (the outer city: new urban district) are selected as case studies, and relevant data are collected in three cases. These data cover mainly travel patterns relating to travelled distances and modal splits to calculate transport-related carbon dioxide emissions. These three study cases are:

Case1: around Hankou railway station (outer city)

Case2: around Wuchang railway station (inner city)

Case3: around Wuhan railway station (High-speed new urban district)

6.2 The Existing issues of the current traffic travel

6.2.1 The contradiction between traffic supply and demand

Traffic congestion is a common phenomenon in large and medium-sized cities in China, and it presents a trend of normalisation and outward spreading. In some of the large and medium-sized cities, traffic congestion is particularly serious during the rush hours for commuters. The cause of traffic congestion lies in the imbalance between urban transport traffic supply and demand. With the acceleration of urbanisation in China and the increase in household income, more residents have chosen to purchase private cars, leading to a sharp increase in private car ownership. High-intensity use and high-density aggregation of private vehicles is the cause of urban traffic congestion. On the other hand, the infrastructure construction of urban transportation is still somewhat inadequate. The development of public transportation is not as fast as the increase in private cars, and the parking facilities are seriously inadequate, further worsening the traffic congestion and parking difficulties. In addition, the unreasonable layout of urban spatial structure and imperfect road network planning are also the causes of traffic congestion.

6.2.2 High carbon dioxide emissions for current travel modes

As the main terminal energy-using sector, the transportation sector consumes energy from various transportation activities. At present, due to factors such as technological and economic development, China's urban transportation still uses fuel as its main driving force. Specifically, it uses gasoline, kerosene, and diesel. The fuel consumption of gasoline, kerosene and diesel in the transportation industry accounted for 70% of the total fuel consumption of the entire society (Liu 2014). The resulting gas emissions and environmental pollution have brought about serious impacts on social ecology and the environment. At the same time, with the continuous development of urban transport, the oil consumption in the transportation industry has only increased, and in recent years there has been a further strengthening trend. As oil reserves, which are non-renewable resources, are continuously being consumed, China will face an increasingly serious energy crisis. It is imperative to adjust and optimise the energy consumption structure of the transportation industry.

Given a specific context, China's automobile industry is still partly in the traditional mode of production. There is still a long way to go before it can be completely transformed from modern and intensive production methods. This shows that China has great potential in the energy saving of automobiles. To effectively achieve energy saving and consumption reduction, efforts should be made to strengthen the technological development of the automobile and promote the use of new energy cars.

6.2.3 Slow development of public transport

Public transport is the most important part of the urban transport system; it is also one of the major means of transport as well as one of the low carbon emission modes. The urban public transport system has scored some progress coupled with the development of the urban economy. However, its overall development is rather slow, and various problems have surfaced along the way, which directly affect the transport infrastructure's efficiency. For example, the infrastructure of urban public transport calls for the improvement; the coverage of the public transport network falls short of residents' demand; efficient transfer cannot be achieved between different transport means, and the departure interval of public transport is too long to meet the residents' traffic demands. Finally, the transition between transfer station, bus, and bicycle stations are not close enough.

6.3 Methods to calculation carbon dioxide emissions from travel activities

6.3.1 Current method

There are two main methods to measure transport-related carbon dioxide emissions. Firstly, total fuel consumption can be calculated based on the annual mileage of various transport modes and the average consumption of fuels per kilometre of corresponding transport modes. Then, by multiplying the CO_2 coefficient of fuels, found in the IPCC (Intergovernmental Panel on Climate Change) guidelines by the total fuel consumption, the carbon dioxide emissions from travel activities can be predicted (Huang et al. 2015). Another method is to use models to calculate carbon emission factors of various transport modes and then to multiply the result by the mileage of corresponding transport modes, and then finally the carbon dioxide emissions from travel activities can be calculated (ibid).

These two methods have their advantages and disadvantages. On the one hand, the first method is relatively authoritative and is more prevalent, but in the actual calculation, it is hard to acquire the fuel type and the corresponding fuel consumption of various modal splits, thus adding difficulty to the calculation. On the other hand, the second method is more flexible and concise because the carbon dioxide emissions can be understood by calculating the emission factors. According to the existing research, there are four types of methods for the calculation of carbon dioxide emissions from travel activities (Brand and Boardman 2008), as presented in Table 6.1. This research is based on the method one.

Table 6.1 Research on the calculation of carbon dioxide emissions from travel activities
Source: Brand and Boardman (2008)

Method	Data	Equation
1	**Traffic activity and disaggregate average emissions factors**	**Emission=f (emission coefficient, traffic activities)**
2	Traffic activity and “official” vehicle specific emissions factors	Emission=f (vehicle manufacturing, fuel, engine, year)
3	Fuel consumption	Emission=f (fuel consumption, type)
4	Fuel expenditure	Emission=f (fuel cost, price, type)

6.3.2 An improved method in this research

To conduct a more accurate calculation of transport-related carbon dioxide emissions from travel activities, this research is based on the annual mileage of various modal splits and non-fixed emission factors. The improved method delivers a more accurate calculation of the carbon dioxide emissions from travel activities. On the one hand, the data of the fuel consumption of different transport vehicles is difficult to obtain, while their annual mileages can be found through large-sample surveys. Therefore, this method overcomes the difficulty of data shortage, making it more flexible to calculate carbon dioxide emissions. On the other hand, given the fact that over the past twenty years, China’s vehicle technology and fuel quality have improved, the carbon dioxide emission factors for transport modes are not constant. Based on the research from the scholar (Liu 2014), this research assumes that the coefficient of carbon dioxide emissions decreases by 0.5% annually, as this more accurately reflects the reality.

People have different choices in transport modes as well as different travel distances.

Therefore, the amount of carbon dioxide emissions varies from one to another. This research calculates carbon dioxide emissions from travel activities according to the different transport modes, distances, and carbon dioxide emission factors. Daily travel modes can be categorised in a three-fold manner: non-motorised transport, transit, and motorised. Transit transport includes buses, rail transit; motorised transport includes private cars, taxis, and e-motorcycles; and non-motorised transport includes cycling and walking, which produce zero carbon dioxide emissions. Considering the accessibility of data, this research discusses the following four types of modes: public buses, the metro, e-motorcycles, taxis, and private cars. The equation for the calculation of carbon dioxide emissions from travel activities is based on the reference Liu (2014 p.36), the equation is:

$$C = \sum_{i} VKT_i * EF_i \qquad (6-1)$$

Where ***C*** stands for the carbon dioxide emissions, in the unit of kg per year; VKT is the annual vehicles kilometres travelled distance, in the unit of km, EF is the carbon emission factors of various transport modes, in the unit of kg per km; i signifies different transport modes.

6.4 Case Study 1: Transport-related carbon dioxide emissions calculation around the Hankou railway station

6.4.1 Data collection description around Hankou railway station

The survey was conducted by interviewing and collecting responses to the questionnaires around Hankou railway station. In May 2016, six post-graduate students of master's degree from Wuhan University of Technology formed 2- or 3-person teams and were evenly distributed among the study areas. They investigated the study area by interviewing people mainly in locations such as entrances, major street intersections, and open spaces like the squares. Some people refused to participate in this survey because they were in a rush to get to work, perhaps worrying about their security. Three categories of the survey were collected, relating to socioeconomic characteristics of the respondents, travel patterns of the interviewees, and self-evaluation on travelling.

6.4.2 Transport-related carbon dioxide emissions calculation

Transport-related carbon dioxide emissions from residential buildings

According to Equation 6-1, transport-related carbon dioxide emissions from residential buildings around Hankou station can be predicted. This study uses the emission factors from Beijing and Shanghai as the basic reference to calculate carbon emission factors for different transport modes in Wuhan due to the lack of emission data for Wuhan. Table 6.2 illustrates the emission factors of four transport modes in the year of 2006 based on the city of Beijing and Shanghai as a reference.

Table 6.2 Reference-based carbon dioxide emissions factors (EF_i) for different transport modes in the year 2006

Transport modes	Public bus	Underground	Taxi	Cars	E-motor
CO_2 emissions（kg/km）	1.065	2.165	0.235	0.215	-----

Source: Zhao et al. 2009. Resident Travel Modes and CO_2 Emissions by Traffic in Shanghai City, Research of Environmental Sciences, 22 (6) 747-752; Liu, W. 2014. Influence Factors and Guidance Strategy of Low Carbon Travel for Urban Resident in China, PhD Dissertation from Beijing Institute of Technology, P 39.

However, for the carbon emission factors of the e-motorcycle, there are limited references to perform the calculation. Therefore, for the calculation of emission factor of e-motor, based on Ni (2009), was used.

Taking the 48V, 12Ah new battery employed in e-motorcycle, as an example, (generally, the power capacity of batteries in the e-motorcycle from China has this capacity), the emission factors calculation is as follows:

- Battery power: 48V * 12Ah = 576 Wh = 0.576 kWh;
- Assumption of the lead-acid battery charging efficiency is about 90%, so the charging power consumption is 0.576 / 90% = 0.64 kWh;
- The assumption of the single longest mileage of the new e-motorcycle is about 50 km. As a result, power consumption in 100 km is: 100 * 0.64 / 50 = 1.28 kWh.

The above method for calculating carbon emission factors for e-motorcycles is based on the newly bought e-motorcycle. However, the power consumption depends on the actual condition. Riding habits, different loads, and different terrains can result in varying levels of energy consumption.

In order to account for this, this work also calculates the carbon emission factor for the two-year used e-motorcycles and then finds the mean carbon emission factors of the two.

Battery power: 48V * 12Ah = 576 Wh = 0.576 kWh;

An assumption of the lead-acid battery charging efficiency is about 50%, so the charging power consumption is 0.576 / 50% = 1.15 kWh;

An assumption of the single longest mileage of the two-year used e-motorcycle is about 30km, as a result, the power consumption in 100 km is: 100 * 1.15 / 30 = 3.83kWh.

Consequently, according to the above two steps for calculating the emission factor of e-motorcycle for 100 km, the final emission factor can be calculated by the mean value of the above two steps by the equation: （1.28+3.83）/2=2.6 kWh. Based on the fact that the coal generates 78% of electricity in China, the conversion coefficient from coal electricity to carbon dioxide emissions is 0.92 (Ni 2009); **therefore, carbon dioxide emissions for the e-motorcycle in 1 km is 2.6×0.01×0.92 ×0.78=0.019kg/km**

As mentioned before, considering the rapid evolution of the technology in the transport, carbon emission factors need regular revision, i.e. every 3 to 5 years. As a result, this research adopts the improved method of the calculation on carbon emission factors, if the carbon emission factor decreases by 0.5% annually, this more accurately reflects the reality. The updated carbon emission factors for different transport modes are presented in table 6.3:

Table 6.3 The updated emission factors in the year 2016 adopted in this research

Transport modes	Public bus	Underground	Taxi	Cars	E-motorcycle
CO_2 emissions（kg/km）	1.013	2.059	0.224	0.204	**0.019**

According to the investigation, there were around 1700 people from residential buildings (detailed information refers to Chapter 5: section 5.2.1). 72 samples were collected from residential buildings, and the valid sample was 60 by motor vehicle, accounting for around 83% shown in Table 6.4. Figure 6.1 shows the proportional choice of mode for the people based in the residential buildings.

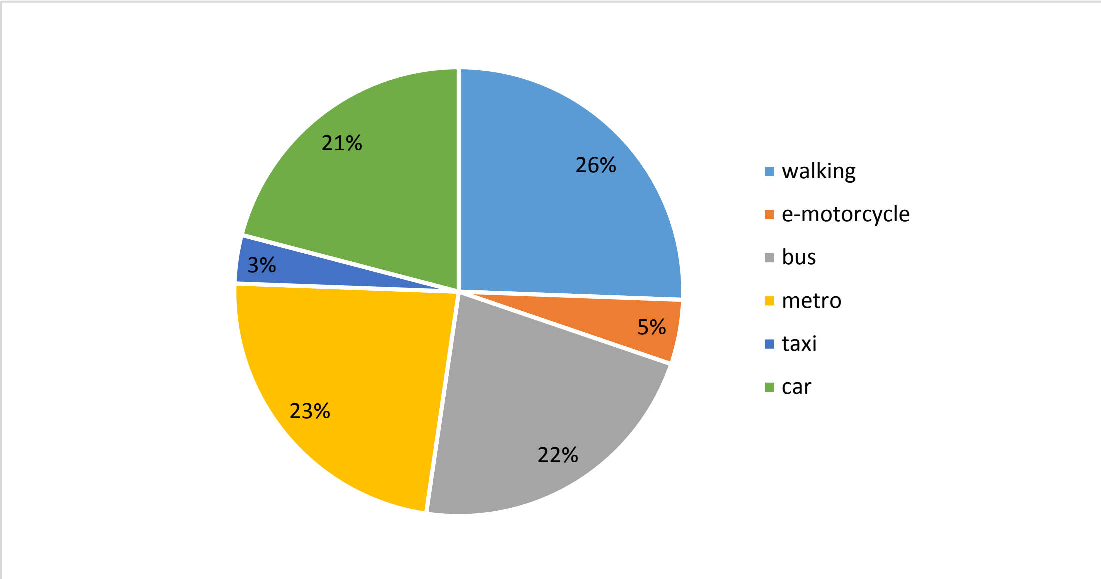


Figure 6.1 Modal splits distribution from residential buildings around Hankou railway station

According to Fig. 6.1, most people choose to walk (26%) as their travel mode, followed by the metro (23%), and then bus (22%). A small proportion of people take by taxi (3%), but more people tend to use private cars (21%). Table 6.4 presents the basic information of distance travelled from the sample by their mode of travel.

Table 6.4 Daily distance travelled by different modes from residential buildings in samples

Transport modes	Daily total travelled distance from samples (km)	No. of samples
Public bus	335	21
Underground	317	21
Taxi	86	3
Private car	326	11
E-motor	74	4

An assumption of this research is made that the sample from the transport mode is independent. For instance, there are 21 samples from the public mode, which means that these people from 21 samples will not share the same public modes. Carbon dioxide emissions can thus be calculated as follows:

Carbon dioxide emissions per capita per day due to each transport mode =daily distance travelled by corresponding mode * corresponding emission factor/passenger capacity of corresponding transport mode.

Carbon dioxide emissions per capita per year due to each transport mode =daily carbon dioxide emissions per capita per day due to each transport mode *365 days.

Therefore, according to the surveyed data of vehicle travelled distance, the emission factors and the above equation, daily and annual total transport carbon dioxide emissions per capita is calculated and presented in Table 6.5 and Table 6.6 respectively.

Table 6.5 The calculation process for daily and annual transport carbon dioxide emissions from residential buildings in samples

Transport modes	Daily total transport carbon dioxide emissions （kg/day/capita）	Description	Annual total transport carbon dioxide emissions （kg/year/capita）	Description
Public bus	335.4× 1.013 /80 /21 =0.20	daily total distance travelled by bus × bus carbon emission factor/passenger capacity for the bus/No. of the sample travelling by bus	0.20×365=73.82	Daily total transport carbon dioxide emissions by public bus × 365

Underground	317.4×2.059 /2280 /21 =0.014	daily total distance travelled by underground × underground carbon emission factor/passenger capacity for the underground at the B level /No. of the sample travelling by metro	0.014×365=4.98	Daily total transport carbon dioxide emissions by underground × 365
Taxi	86×0.224/3 =6.42	daily total distance travelled by taxi×taxi carbon emission factor /No. of the sample travelling by taxi	6.42× 365=2343.79	Daily total transport carbon dioxide emissions by taxi × 365
Private car	326 ×0.204/11 =6.05	daily total distance travelled by private cars×private car carbon emission factor /No. of the sample travelling by private car	6.05× 365=2206.72	Daily total transport carbon dioxide emissions by private cars×365
E-motor	74 ×0.019/4 =0.35	daily total distance travelled by×e-motor carbon emission factor /No. of the sample travelling by e-motor	0.35×365=128.30	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.6 The summary of per capita carbon dioxide emissions by different transport modes from residential buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）
Public bus	0.20	73.82
Underground	0.014	4.98
Taxi	6.42	2343.79
Private car	6.05	2206.72

E-motor	0.35	128.30

*Note: this research regards the passenger capacity for the public bus as 80 people; metro passenger capacity as 285 per compartment, and usually the Wuhan underground has eight compartments, so the passenger capacity for underground is 285*8=2280 people.*

Finally, **according to the percentage of modal splits from Fig. 6.1 and the corresponding annual total transport carbon dioxide emissions per capita from each transport mode in Table 6.6,** the annual per capita transport-related carbon dioxide emissions from samples can be calculated as follows: **73.82*22%+4.98*23%+2344*3%+2207*21%+128*5%= 557 kg CO_2 /year/capita**

Furthermore, for the data in this research, there are 426 households in the He Jiadun community and 210 households in the Donghang community, and their household occupancy rate is 93.2% and 90%. Three people are generally occupied in each household based on the survey. Therefore, the total number of people in the study area is (426*93.2%+210*90%) *3=1761 people. Consequently, the total annual carbon dioxide emissions by residents due to the mobility from the study area can be predicted: Annual per capita carbon dioxide emissions from samples * a number of people in the study area * proportion of people by vehicle=557kg*1761 people*69%=676,805kg=677 ton. This is summarised in Table 6.7, which uses different units.

Table 6.7 Total carbon dioxide emissions due to travel activities from residential buildings

Annual per capita carbon dioxide emissions from samples（kg /year/capita）	557	73.82*22%+4.98*23%+2344*3%+2207*21%+128*5%

Annual total carbon dioxide emissions from the study area（kg /year）	676,805	Annual per capita carbon dioxide emissions* number of people in the study area* proportion of people by vehicle=557kg*1761people*69%=676,805
Annual per square metre carbon dioxide emissions in the study area（kg/m^2 /year）	9.1	Total carbon dioxide emissions/ residential buildings floor area =676,805/75,073

Transport-related carbon dioxide emissions from public buildings (office, commercial)

For transport-related carbon dioxide emissions from public buildings, the emission factors from different transport modes can be found in Table 6.3. According to the survey, there were around 2000 people from these buildings, and ultimately 63 valid samples. The distribution of transport modes in the study area is shown in Fig. 6.2:

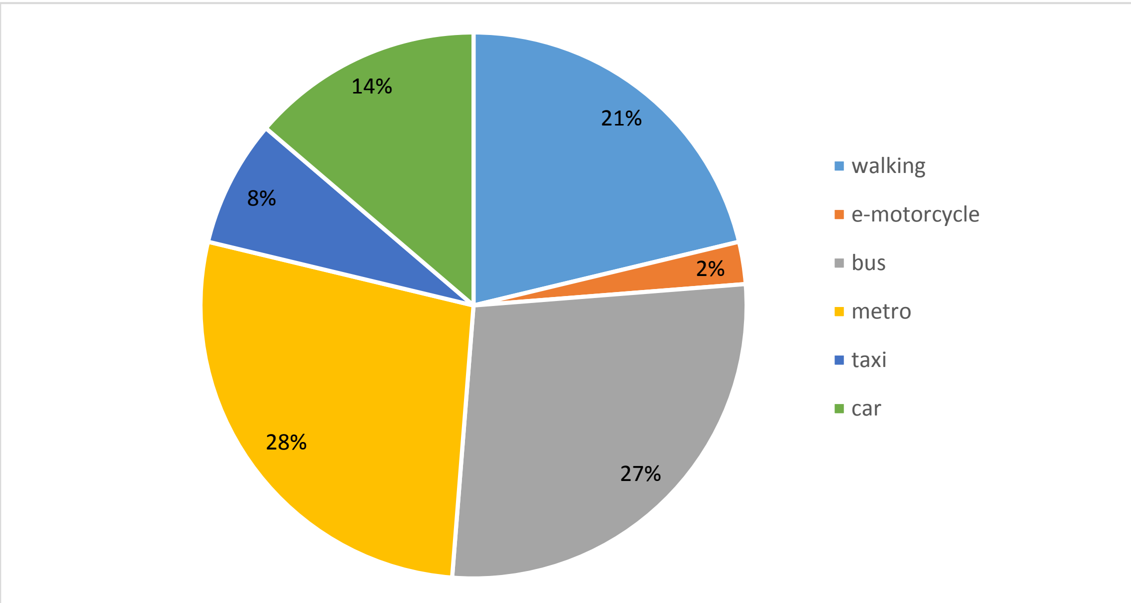


Figure 6.2 Modal splits distribution from public buildings around Hankou railway station

Figure 6.2 shows the modal split distribution from public buildings, and it indicates that most people take the underground and bus as their travelling modes, representing 28% and 27%, respectively. 21% of people tend to walk as their primary travel mode. As a result, the daily and annual carbon dioxide emissions per capita due to different transport modes can be predicted.

Table 6.8 presents the vehicles travelled distance from the valid sample in the public buildings. Table 6.9 and Table 6.10 illustrates the calculation process for carbon dioxide emissions and the summary, respectively.

Table 6.8 Daily distance travelled by different modes from public buildings in samples

Transport modes	Daily total distance travelled from the sample (km)	No of samples
Public bus	520.4	22
Underground	630	22
Taxi	92	6
Private car	271.2	11
E-motor	20	2

Table 6.9 The calculation process for daily and annual transport carbon dioxide emissions from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita （kg/day/capita）	Description	Annual total transport carbon dioxide emissions per capita （kg/year/capita）	Description
Public bus	520.4×1.013 /80 /22 =0.30	daily total distance travelled by public bus from public buildings× corresponding emission factors/ bus passenger capacity/ samples	0.30×365=109.32	Daily total transport carbon dioxide emissions by public bus × 365

Underground	630×2.059/2280/22 =0.026	daily total distance travelled by underground from public buildings× corresponding emission factors/ underground passenger capacity/ samples	0.026×365=9.44	Daily total transport carbon dioxide emissions by underground × 365
Taxi	92×0.224/6=3.43	daily total distance travelled by taxi from public buildings× corresponding emission factors/ samples	3.43×365=1250.92	Daily total transport carbon dioxide emissions by taxi × 365
Private car	271.2×0.204/11 =5.04	daily total distance travelled by private cars from public buildings× corresponding emission factors/ samples	5.04×365=1840.18	Daily total transport carbon dioxide emissions by private cars×365
E-motor	20×0.019/2=0.19	daily total distance travelled by e-motor from public buildings× corresponding emission factors/ samples	0.19×365=69.35	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.10 The summary of per capita carbon dioxide emissions by different transport modes from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）
Public bus	0.30	109.32
Underground	0.026	9.44
Taxi	3.43	1250.92
Private car	5.04	1840.18
E-motor	0.19	69.35

Finally, annual per capita transport-related carbon dioxide emissions（kg CO_2/year/capita）in public buildings from the sample can be predicted as follows

109.32*27%+9.44*28%+1250.92*8%+1840.18*14%+69.35*2%=391kgCO$_2$ /year/capita

According to the survey, the total number of people from public buildings is around 2054, and 77% of these people use motor vehicle as their primary transport. Therefore, the total transport-related carbon dioxide emissions from public buildings in the study area can be calculated: Annual per capita carbon dioxide emissions from samples * number of people in the study area * the proportion of people by vehicle=391kg*2054 people*77%=618,398 kg CO_2. This information is described in table 6.11:

Table 6.11 Total carbon dioxide emissions due to travel activities from public buildings

Annual per capita carbon dioxide emissions from samples （kg/year/capita）	391	109.32*27%+9.44*28%+1250.92*8%+ 1840.18*14%+69.35*2%
Annual total carbon dioxide emissions from the study area （kg/year）	618,398	Annual per capita carbon dioxide emissions* number of people in the study area* proportion of the people by vehicle=391kg*2054 people*77%=618,398
Annual per square metre carbon dioxide emissions（kg/m^2 /year）	7.4	Total carbon dioxide emissions/ public building floor area =618,398/84,006

As a result, the amount of annual transport-related carbon dioxide emissions is the carbon dioxide emissions generated by residential buildings (676,805 kg) and public buildings (618,398 kg). The annual total amount is around 1295 ton, with around 16.5 (7.4+9.1=16.5) kg/m^2 /year.

6.5 Case Study 2: Transport-related carbon dioxide emissions calculation around the Wuchang Railway Station

6.5.1 Data collection description around Wuchang railway station

For the case study 2: Wuchang railway station surroundings, the on-site survey was carried out from 5th July to 8th July (2016) by four students from Wuhan University of Technology. Due to the lack of the surveyors, the investigation was conducted on different days. Like the previous case study, three aspects relating to the socio-economic characteristics of the respondents, travel patterns of the interviewees, and self-evaluation on travelling, are recorded. The survey was performed in residential and public buildings. The main purpose was to identify the occupants' travel purpose, VKT, and travel mode choice.

6.5.2 Transport-related carbon dioxide emissions calculation

<u>Transport-related carbon dioxide emissions from residential buildings</u>

According to the survey, there are 536 households with around 1200 people for residential use (detailed information refers to Chapter 5: Case 2). For this investigation, there are 81 valid samples from residential buildings, being 7% of the total population. The detailed information about the distribution of people by different transport modes from residential buildings is shown in Fig. 6.3.

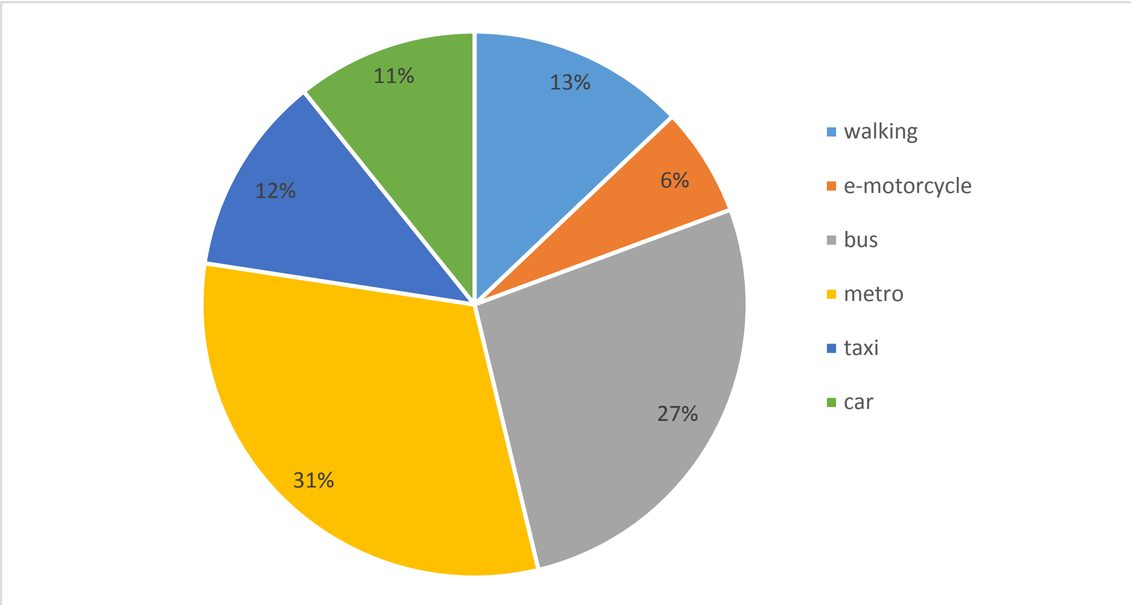


Figure 6.3 Modal splits distribution from residential buildings around Wuchang railway station

It shows that most of the people (58%) from residential buildings use public transport mode (bus and metro), followed by walking (13%) and then taxi (12%). Table 6.12 is the surveyed data of vehicle-travelled distance from the valid sample.

Table 6.12 Daily distance travelled by different modes from residential buildings in samples

Transport modes	Daily total distance travelled from samples (km)	No of samples
Public bus	904.2	25
Underground	1012.4	29
Taxi	280.8	11
Private car	370	10
E-motor	169.6	6

Based on the data in Table 6.12, the daily total transport carbon dioxide emissions per capita is calculated and summarised in table 6.13 and table 6.14:

Table 6.13 The calculation process for daily and annual transport carbon dioxide emissions from residential buildings in samples

Transport modes	Daily total transport carbon dioxide e missions per capita from samples（kg/day/capita）	Description	Annual total transport carbon dioxide emissions per capita from samples（kg/year/capita）	Description
Public bus	904.2×1.013 /80 /25 =0.46	daily total distance travelled by public bus from public buildings× corresponding emission factors/ bus passenger capacity/ samples	0.46×365=167.16	Daily total transport carbon dioxide emissions by public bus × 365
Underground	1012.4×2.059/2280/29 =0.032	daily total distance travelled by underground from public buildings× corresponding emission factors/ underground passenger capacity/ samples	0.032×365=11.51	Daily total transport carbon dioxide emissions by underground × 365
Taxi	280.8×0.224/11 =5.72	daily total distance travelled by taxi from public buildings× corresponding emission factors/ samples	5.72×365=2087.11	Daily total transport carbon dioxide emissions by taxi × 365
Private car	370×0.204/10 =7.55	daily total distance travelled by private vehicles from public buildings× corresponding emission factors/ samples	7.55×365=2755.02	Daily total transport carbon dioxide emissions by private cars×365
E-motor	169.6 ×0.019/6 =0.54	daily total distance travelled by e-motor from public buildings× corresponding emission factors/ samples	0.54×365=196.03	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.14 Summary of per capita carbon dioxide emissions by different transport modes from residential buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）

Public bus	0.46	167.16
Underground	0.032	11.51
Taxi	5.72	2087.11
Private car	7.55	2755.02
E-motor	0.54	196.03

Finally, annual per capita carbon dioxide emissions（kg CO_2 /year/capita）in residential buildings from samples can be calculated:

167.16*27%+11.51*31%+2087.11*12%+2755.02*11%+196.03*6%=614 kg CO_2 /year/capita

The annual transport-related carbon dioxide emissions from residential buildings in the study area can then be predicted as follows: annual per capita carbon dioxide emissions from sample* number of people in the study area* the proportion of the people by vehicle=614kg*1215 people*81%=604,268kg=604 ton. These calculation processes are detailed in Table 6.15.

Table 6.15 Total annual carbon dioxide emissions due to travel activities from residential buildings

Annual per capita carbon dioxide emissions from samples（kg/year/capita）	614	167.16*27%+11.51*31%+2087.11*12%+ 2755.02*11%+196.03*6%=614
Annual total carbon dioxide emissions from the study area（kg/year）	604,268	Annual per capita carbon dioxide emissions* number of people in the study area* proportion of the people by vehicle= 614kg*1215 people*81%=604,268
Annual per square metre carbon dioxide emissions（kg/m^2 /year）	12.7	Total carbon dioxide emissions/ residential buildings floor areas=604,268/47,476

<u>Transport-related carbon dioxide emissions from public buildings (office,</u>

commercial)

According to the data of this research, the number of people occupying public buildings is around 2000 (detailed information refers to Chapter 5: Case 2). Among these people, there were 97 valid samples from public buildings by vehicle (NMM and Driving modes). The detailed information on transport modes distribution in the study area can be shown in Fig. 6.4.

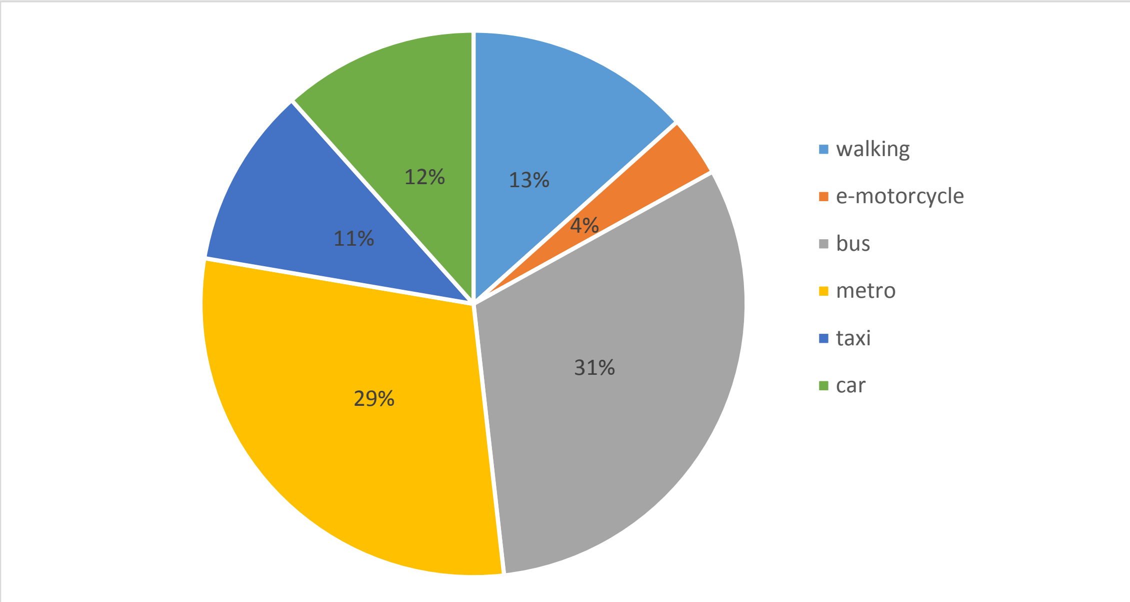


Figure 6.4 Modal splits distribution from public buildings around Wuchang railway station

According to Figure.6.4, most people prefer to take public buses and the underground as their primary transport modes, accounting for 31% and 29%, respectively. The smallest proportion is the e-motorcycle, accounting for only 4% of the people surveyed. Table 6.16 presents the vehicle-travelled distance from the public buildings in the valid samples

Table 6.16 Daily distance travelled by different modes from public buildings in samples

Transport modes	Daily total distance travelled from samples (km)	No of samples
Public bus	750.4	35
Underground	716.4	33
Taxi	248.8	12
Private car	306.6	13
E-motor	30	4

The associated carbon dioxide emissions are calculated and summarised in Table 6.17 and 6.18:

Table 6.17 The calculation process for daily and annual transport carbon dioxide emissions from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita from samples （kg/day/capita）	Description	Annual total transport carbon dioxide emissions per capita from samples （kg/year/capita）	Description
Public bus	750.4×1.013 /80 /35=0.27	daily total distance travelled by public bus from public buildings× corresponding emission factors/ bus passenger capacity/ samples	0.27×365=99.09	Daily total transport carbon dioxide emissions by public bus × 365
Underground	716.4×2.059/2280/33 =0.02	daily distance travelled by underground from public buildings× corresponding emission factors/ underground passenger capacity/ samples	0.02×365=7.16	Daily total transport carbon dioxide emissions by underground × 365
Taxi	248.8×224/12=4.64	daily distance travelled by taxi from public buildings × corresponding emission factors/ samples	4.64×365=1695.16	Daily total transport carbon dioxide emissions by taxi × 365

Private car	306.6×0.204/13 =4.81	daily distance travelled by private car from public buildings× corresponding emission factors/ samples	4.81×365=1756.11	Daily total transport carbon dioxide emissions by private car×365
E-motor	30 ×0.019/4 =0.14	daily distance travelled by e-motor from public buildings×corresponding emission factors/ samples	0.14×365=52.01	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.18 Summary of per capita carbon dioxide emissions by different transport modes from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）
Public bus	0.27	99.09
Underground	0.02	7.16
Taxi	4.64	1695.16
Private car	4.81	1756.11
E-motor	0.14	52.01

Finally, the annual per capita carbon dioxide emissions（kg CO_2/year/capita） from public buildings in samples can be calculated:

99.09*31%+7.16*29%+1695.16*11%+1756.11*12%+52.01*4%=432kg CO_2/year/capita

The annual transport carbon dioxide emissions from public buildings in the study area can then be predicted: annual per capita carbon dioxide emissions* a number of people in the study area*the proportion of the people by vehicle=432kg*2000 people*83%=717,120 kg=717 ton. These results are outlined in Table 6.19

Table 6.19 Total annual carbon dioxide emissions due to travel activities from public buildings

Annual per capita carbon dioxide emissions from samples （kg/year/capita）	432	99.09*31%+7.16*29%+1695.16*11%+1756.11*12%+52.01*4%=432
Annual total carbon dioxide emissions from study areas（kg/year）	717,120	Annual per capita carbon dioxide emissions* number of people in the study area*the proportion of the people by vehicle=432kg*2000 people*83%=717,120
Annual per square metre carbon dioxide emissions（kg/m^2 /year）	5.7	Total carbon dioxide emissions/public building floor area=717,120/126,042

Finally, annual transport-related carbon dioxide emissions from residential buildings and public buildings in the study area are predicted. The results 1321 (604,268kg +717,120 kg) ton annual transport-related carbon dioxide emissions, with around 18.4 (12.7+5.7) kg/m^2 /year.

6.6 Case Study 3: Transport-related carbon dioxide emissions calculation around the Wuhan Station

6.6.1 Data collection description from residential buildings around Wuhan Station

For the case study three—Wuhan station surroundings一the questionnaires were carried out on 15 July 2016 in the meeting held at the Ganghua community area. This community area is mainly for residential use, and there were almost no any commercial or office buildings. This community lies around three to four kilometres from Wuhan station. This community was built in around the year 2002. Just as in the previous case studies, three aspects: the socio-economic characteristics of the respondents, travel patterns of the interviewees, and self-evaluation of travelling, are recorded. The main purpose was to identify their travel purpose, VKT, and mode choices.

6.6.2 Transport-related carbon dioxide emissions calculation

Transport-related carbon dioxide emissions from residential buildings

From the on-site survey, there were around 760 households, with an occupancy rate of about 80%, meaning that about 610 families were actually from the residential buildings. The total number of the people can be estimated to be around 1800 by following the survey of three people in each household. For this investigation, there were 72 valid samples from residential buildings by vehicle, representing around 5% of the total population. The detailed information about the distribution of people by different transport modes from residential buildings is shown in Fig. 6.5:

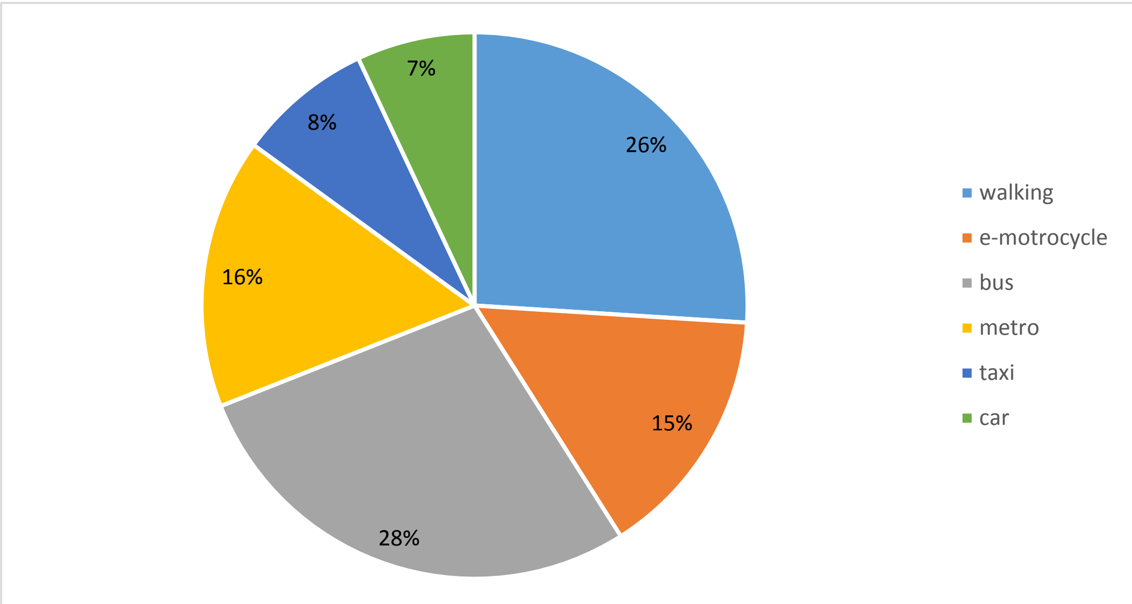


Figure 6.5 Modal splits distribution from residential buildings around Wuhan station

As can be seen from Fig.6.5, most of the people (44%) take public transport modes (bus and underground) as their main travelling modes from residential buildings, followed by walking (26%) and then e-motorcycle (15%). The remaining 15% people travel are by car or taxi, but the proportion is almost the same. Table 6.20 presents the daily vehicle-travelled distance by different modes from the valid sample in residential buildings.

Table 6.20 Daily distance travelled by different modes from residential buildings in samples

Transport modes	Daily total distance travelled from samples (km)	No of samples
Public bus	872.4	27
Underground	556	16
Taxi	267.2	8
Private car	134.6	7
E-motor	860	14

According to the surveyed data, the daily transport-related carbon dioxide emissions per capita can be calculated and summarised in Table 6.21 and Table 6.22:

Table 6.21 The calculation process for daily and annual transport carbon dioxide emissions from residential buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita （kg/day/capita）	Description	Annual total transport carbon dioxide emissions per capita （kg/year/capita）	Description
Public bus	847.2×1.013 /80 /27 =0.41	daily total distance travelled by public bus from public buildings× corresponding emission factors/ bus passenger capacity/ samples	0.41×365=149.36	Daily total transport carbon dioxide emissions by public bus × 365

Underground	556×2.059/2280/16 =0.031	daily total distance travelled by underground from public buildings× corresponding emission factors/ underground passenger capacity/ samples	0.031×365=11.45	Daily total transport carbon dioxide emissions by underground × 365
Taxi	267.2×0.224/8 =7.48	daily total distance travelled by taxi from public buildings× corresponding emission factors/ samples	7.48×365=2730.8	Daily total transport carbon dioxide emissions by taxi × 365
Private car	134.6×0.204/7 =3.92	daily total distance travelled by private car from public buildings× corresponding emission factors/ samples	3.92×365=1431.8	Daily total transport carbon dioxide emissions by private car×365
E-motor	860 ×0.019/14 =1.17	daily total distance travelled by e-motor from public buildings× corresponding emission factors/ samples	1.17×365=426.01	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.22 Summary of per capita carbon dioxide emissions by different transport modes from residential buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）
Public bus	0.41	149.36
Underground	0.031	11.45
Taxi	7.48	2730.8
Private car	3.92	1431.8
E-motor	1.17	426.01

Finally, annual per capita carbon dioxide emissions（kg CO_2 /year/capita）generated from residential buildings in the sample can be predicted:

149.36*28%+11.45*16%+2730.8*8%+1431.8*7%+426.01*15%=426 kg CO_2 /year/capita

The annual total transport carbon dioxide emissions from residential buildings in the study area can then be predicted: Annual per capita carbon dioxide emissions* a number of people in the study area*the proportion of the people by vehicle=426 kg*1830 people*59%=459,952kg=460 ton. This process is detailed in Table 6.23.

Table 6.23 Total transport annual carbon dioxide emissions due to travel activities from residential buildings

Annual per capita carbon dioxide emissions from samples （kg/year/capita）	426	149.36*28%+11.45*16%+2730.8*8%+1431.8*7%+426.01*15%= 426
Annual total carbon dioxide emissions from study area（kg/year）	459,952	Annual per capita carbon dioxide emissions* number of people in the study area* proportion of the people by vehicle=426kg*1830 people*59%=459,952
Annual per square metre carbon dioxide emissions（kg/m^2 /year）	5.4	Total carbon dioxide emissions/ residential building floor areas=459,952/85,256

Transport-related carbon dioxide emissions from Public buildings

According to the survey carried out on 18th July on the WuShang ZhongYuan Mall, the mall is a city complex combined with recreation, commercial, and shopping buildings, etc. There are around 2000 people, including the population mobility from the estimate on the site. In this survey, there were more than 130 samples collected, accounting for around 7% of the total population. The detailed information about the distribution of people by different transport modes from public buildings is shown in Fig. 6.6:

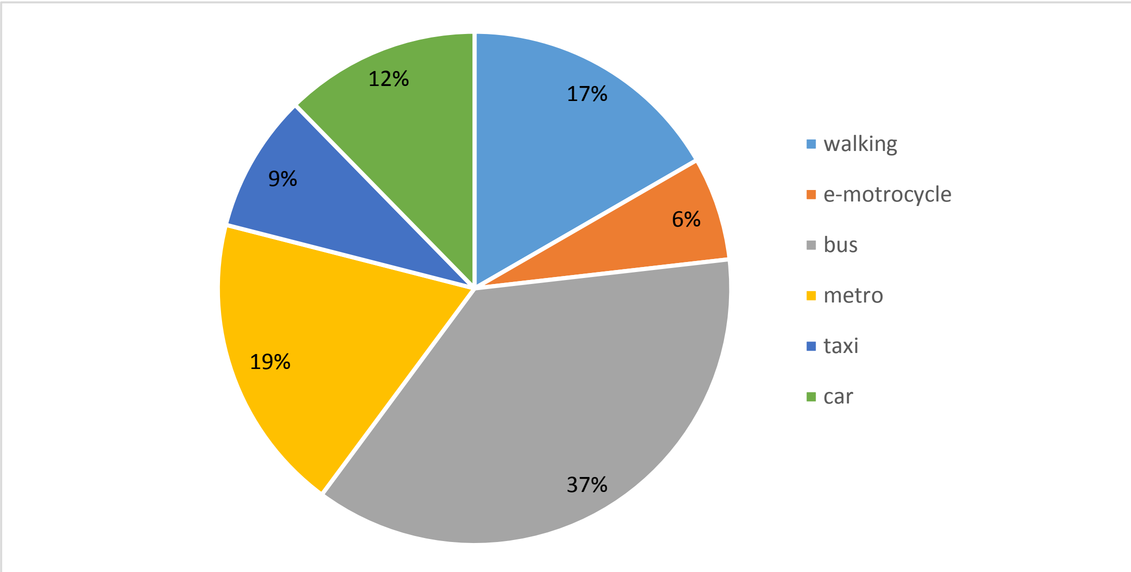


Figure 6.6 Modal splits distribution from public buildings around Wuhan station

Figure 6.6 indicates that most people (37%) take the bus as their main travel mode, followed by the underground (19%), and then walking (17%). These values combined with the travelled distance can be used to calculate the daily transport carbon dioxide emissions per capita by different modes. The following table presents the distance travelled by vehicle from the sample.

Table 6.24 Daily distance travelled by different modes from public buildings in samples

Transport modes	Daily total distance travelled from the sample (km)	No of samples
Public bus	1174.4	51
Underground	883.6	26
Taxi	648.8	12
Private car	550.2	17
E-motor	94	9

The daily transport-related carbon dioxide emissions per capita can then be summarised in Tables 6.25 and 6.26.

Table 6.25 The calculation process for daily and annual transport carbon dioxide emissions from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita (kg/day/capita)	Description	Annual total transport carbon dioxide emissions per capita (kg/year/capita)	Description
Public bus	1174.4×1.013 /80 /51 =0.29	daily total distance travelled by public bus from public buildings× corresponding emission factors/ bus passenger capacity/ samples	0.29×365=106.43	Daily total transport carbon dioxide emissions by public bus × 365
Underground	883.6 ×2.059/2280/26 =0.031	daily total travelled distance by underground from public buildings× corresponding emission factors/ underground passenger capacity/ samples	0.031×365=11.20	Daily total transport carbon dioxide emissions by underground × 365
Taxi	648.8×0.224/12 =12.11	daily total distance travelled by taxi from public buildings× corresponding emission factors/ samples	12.11× 365=4420.49	Daily total transport carbon dioxide emissions by taxi × 365
Private car	550.2×0.204/17=6.60	daily total distance travelled by private car from public buildings× corresponding emission factors/ samples	6.60×365=2409.88	Daily total transport carbon dioxide emissions by private car×365
E-motor	94 ×0.019/9 =0.2	daily total distance travelled by e-motor from public buildings× corresponding emission factors/ samples	0.2×365=72.43	Daily total transport carbon dioxide emissions by e-motor×365

Table 6.26 Summary of per capita carbon dioxide emissions by different transport modes from public buildings in samples

Transport modes	Daily total transport carbon dioxide emissions per capita with each transport mode from samples（kg/day/capita）	Annual total transport carbon dioxide emissions per capita with each transport mode from samples（kg/year/capita）
Public bus	0.29	106.43
Underground	0.031	11.20
Taxi	12.11	4420.49
Private car	6.60	2409.88
E-motor	0.20	72.43

Finally, annual per capita carbon dioxide emissions（kg CO_2/year/capita）from public buildings in the sample can be predicted:

106.43*37%+11.20*19%+4420.49*9%+2409.88*12%+72.43*6%=732kg CO_2/year/capita

The annual transport carbon dioxide emissions from public buildings in the study area can then be predicted by the annual per capita carbon dioxide emissions* a number of people in the study area* proportion of people by vehicle=732kg*2000 persons*77%=1,127,280kg=1127 ton. This information is detailed in Table 6.27.

Table 6.27 Total annual carbon dioxide emissions due to travel activities from public buildings

Annual per capita carbon dioxide emissions from samples（kg/year/capita）	732	106.43*37%+11.20*19%+4420.49*9%+2409.88*12%+72.43*6%=732
Total carbon dioxide emissions from study area（kg/year）	1,127,280	Annual per capita carbon dioxide emissions* number of people in the study area* proportion of people by vehicle=732kg*2000 persons*77%=1,127,280

Annual per square metre carbon dioxide emissions（$kg/m^2/year$）	6.3	Total carbon dioxide emissions/ public building floor area=1,127,280/180,000

The total amount of annual carbon dioxide emissions from the transport is the combined total of the carbon dioxide emissions generated by residential buildings and public buildings. This is around 1587 ton/ year (459,952kg +1,127, 280kg), with 11.7 $kg/m^2/year$.

6.7 Results analysis and conclusions

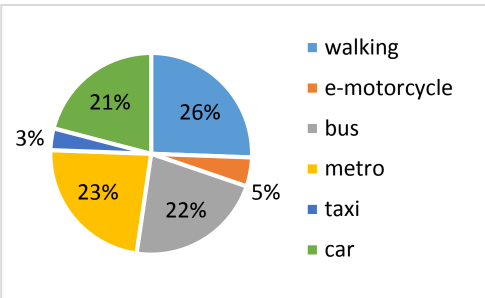
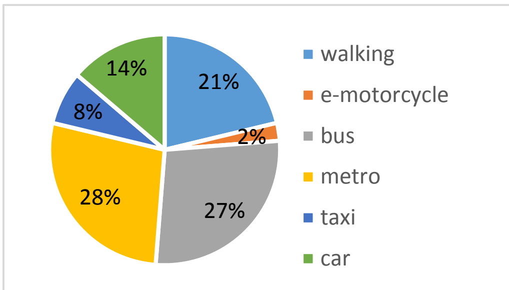
Table 6.28 summarises and compares the transport-related carbon dioxide emissions from three cases discussed in this research. It presents and compares the information relating to the floor-area of different building types, the population size in the study area, the percentage of motor vehicle, and finally the annual transport-related carbon dioxide emissions.

Table 6.28 Summary of transport-related carbon dioxide emissions from three cases

	Residential			Public buildings		
Hankou station (Case 1)	Floor area (m^2)	Population in the study area	Motor vehicle proportion	Floor area (m^2)	Population in the study area	Motor vehicle proportion
	75,073	1761	69%	84,206	2054	77%
Carbon dioxide emissions	676,805 kg/year			618,398 kg/year		
	557 kg/year/capita			**391 kg/year/capita**		
	9.1 $kg/m^2/year$			**7.4 $kg/m^2/year$**		
Wuchang station (Case 2)	Floor area (m^2)	Population in the study area	Motor vehicle proportion	Floor area (m^2)	Population in the study area	Motor vehicle proportion
	47,476	1215	81%	126,042	2000	83%
Carbon dioxide emissions	604,268 kg/ year			717,120 kg/ year		
	614 kg/year/capita			**432 kg/year/capita**		
	12.7 $kg/m^2/year$			**5.7 $kg/m^2/year$**		

Wuhan Station (Case 3)	Floor area (m^2)	Population in the study area	Motor vehicle proportion	Floor area (m^2)	Population in the study area	Motor vehicle proportion
	85,256	1830	59%	180,000	2000	77%
Carbon dioxide emissions	459,952kg/year			1,127,280 kg/ year		
	426kg/year/capita			**732kg/year/capita**		
	5.4 kg/m²/year			**6.3 kg/m²/year**		

Figure 6.7 describes distributions of modal splits from samples in these three cases, and Figure 6.8 compared annual per capita carbon dioxide emissions from three cases. It finds out that annual per capita carbon dioxide emissions from residential buildings in Case 2 were the highest, standing at around 614 kg/ year/capita, followed by 557 kg/ year/capita in Case 1, and 426 kg/ year/capita in Case 3. However, for annual per capita carbon dioxide emissions from public buildings, Case 3 was the highest, followed by Case 2 and Case 1.

	Residential	Public
Case 1		

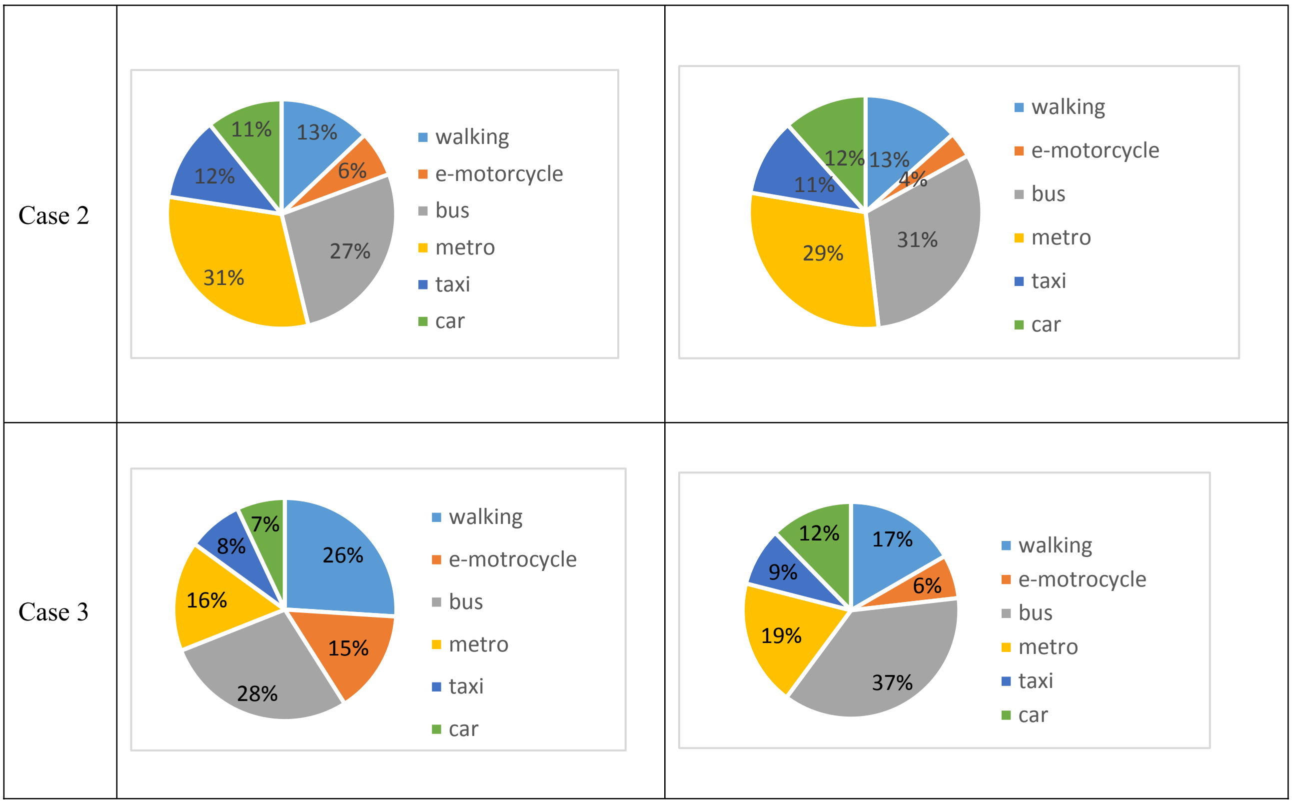


Figure 6.7 Modal splits distribution among three cases

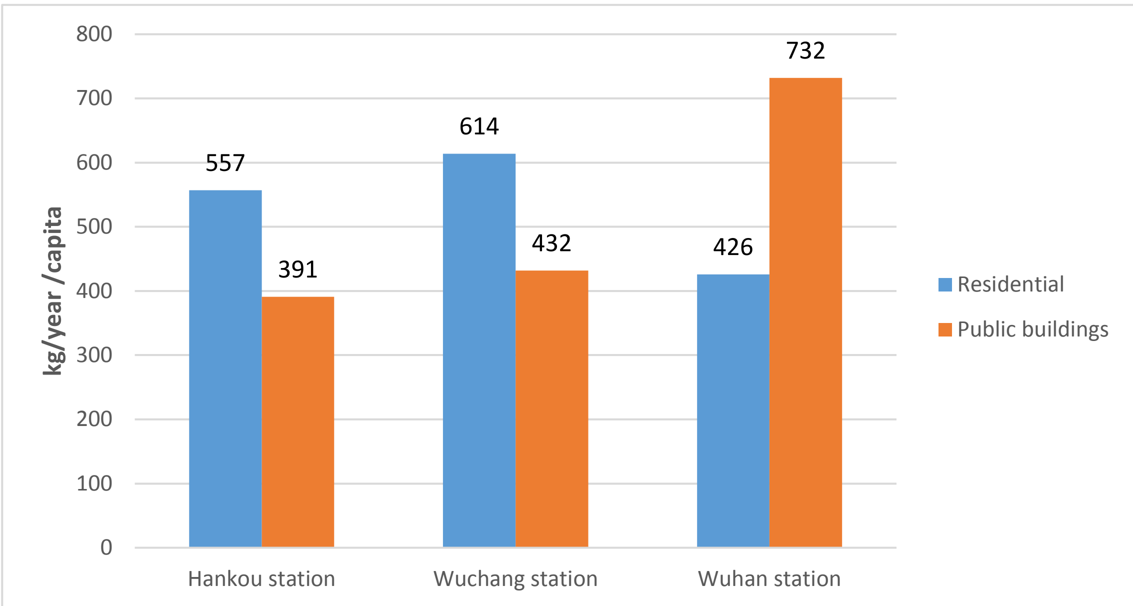


Figure 6.8 Annual per capita transport-related carbon dioxide emissions between residential and public buildings

One of the possible reasons is the distribution of travel modes from these three cases. According to the survey shown in Fig. 6.7, there is 23% of people taking private travel modes (12% taxi plus 11% car) from residential buildings in Case 2. Although people from residential buildings in Case 1 had the highest motorisation rate 24% (3% taxi plus 21% car), these two travel modes were uneven distribution compared to Case 2 from residential buildings. For Case 3, there was 15 % of private travel modes (8% taxi and 7%), and this percentage was largely less than Case 2 (22 %) and Case 1 (24%).

The distribution of the locations is another possible reason. Case 2 is inner-city district and Case 1 is outer city centre. Both districts are better developed, with more than three decades. Infrastructure and public service are available around public buildings from these two Cases; many travel activities can be locally completed. The distribution of public transport nodes is shown in Fig. 6.9, which indicates the rail and public bus are well covered in Case 1 and Case 2. Moreover, the percentage of private travel modes from public buildings in Case 1 and Case 2 was larger than corresponding public buildings (Case 1: 24% vs 22%; Case 2: 22% vs 22%). Therefore, annual per capita carbon dioxide emissions from public buildings in Case 1 and Case 2 are less than those from corresponding residential buildings.

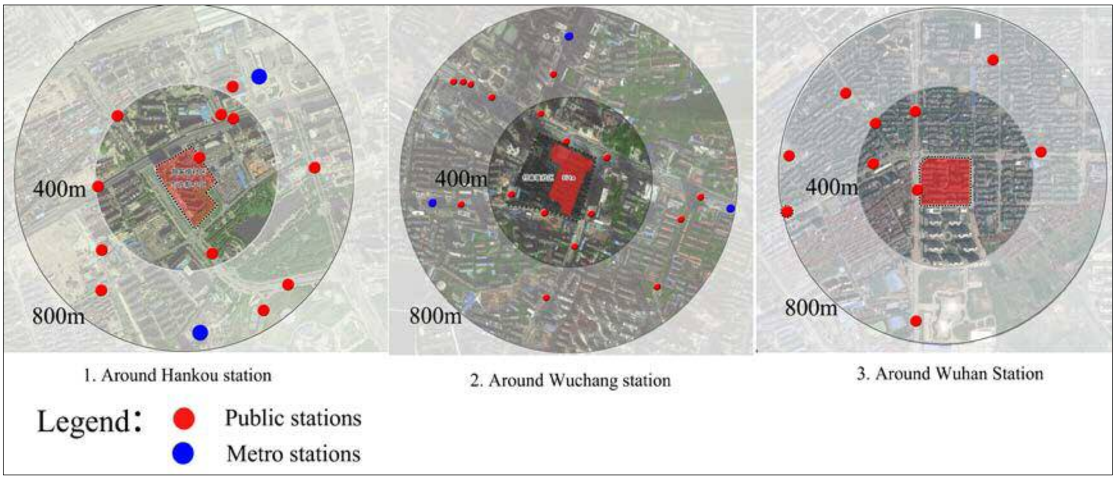


Figure 6.9 The distribution of public transport nodes in three cases

However, annual carbon dioxide emissions from public buildings of Case 3 have the largest value of around 732 kg/ year/capita, and this is far more than those of from Case 2 (432 kg/ year/capita) and Case 1 (391 kg/ year/capita). One possible reason is the status of urban development. For Case 3, this is the new urban district, oriented with high-speed rail development, and it is at the initial stage, less than one decade. Many public services are not available. Rail transits are not covered, and only public routes are available, which can generate more chances to use private cars from public buildings. According to the survey, there was no rail transit available around the Case 3. In other words, many travel activities cannot be complete locally. Moreover, from the modal splits' distribution in Case 3, 21% people are by private modes from public buildings versus 15% people from residential buildings. Therefore, annual per capita transport CO_2 emissions from public buildings are higher than those from residential buildings in Case 3.

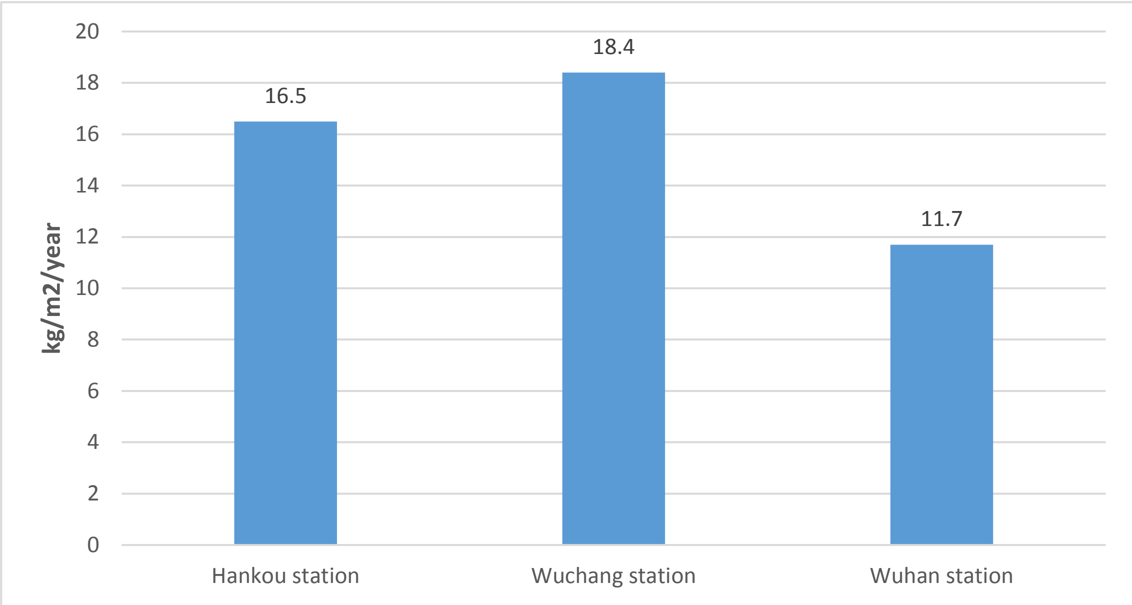


Figure 6.10 Annual transport-related carbon dioxide emissions with each case

To compare CO_2 emissions with building sector, this study converts the units of kg/year/capita from transport-related carbon dioxide emissions to the units of kg/m^2/year shown in Fig. 6.10. The carbon dioxide emissions from both sectors can then be compared.

This chapter has answered the questions

- *"What models can be applied to predict transport-related carbon dioxide emissions from travel activities due to mobilities of users from buildings?"*

This chapter aims to understand and predict transport-related CO_2 emissions using the activities-based transport demand model based on the data from respondents (e.g., travelled distance, modal split) found through on-site surveys. The results not only present the transport-related carbon dioxide emissions but also recognise the differences in carbon dioxide emissions from different building types and locations. Additionally, the quantitative assessment helps to identify the mode preferences from travellers in various building types around different locations. Several important conclusions can be drawn from these findings:

Firstly, based on the calculation of emission factors from different transport modes, it shows that the underground, public buses, and e-motorcycles have the lowest daily per capita transport-related carbon dioxide emissions, and their values are significantly less than those of private cars and taxis. Therefore, travelling by underground, public bus, and e-motorcycles, should be strongly promoted for commuting considering the low CO_2 emissions.

Secondly, compared with three cases, annual carbon dioxide emissions from residential buildings are higher than those of public buildings in the well-developed area. This is because public services and infrastructures are provided and available, and many travel activities from public buildings can be fulfilled locally. This phenomenon can be well observed in three cases. Carbon dioxide emissions from public buildings in Case 1 and Case 2 are noticeably less than those of from Case 3 as the land development in Case 3 is in its early development stage, and the public transport services and infrastructure are limited and insufficient. In contrast, public buildings in Case 1 and Case 2 are very close to the CBD, with high accessibility and more public transport services available.

Thirdly, to understand the transport-related carbon dioxide emissions, this research uses the activities-based transport demand model with the improved emission factors that the carbon emission factor decreases by 0.5% annually, as this more accurately reflects the reality. Therefore, the results are more accurate compared with the previous studies.

Chapter 7 Parametric and Regression Analysis of Selected Factors Affecting Energy Consumption and Associated Carbon Dioxide Emissions on Building Clusters and Travel Activities

7.1 Introduction

Chapter 5 and 6 focus on the quantification of carbon dioxide emissions from buildings and the transport sector, respectively. This chapter answers the following question:

“To what extent do the selected factors affect energy consumption and associated carbon dioxide emissions.”

To answer the questions above, the parametric and regression analysis explore the relationship between these selected factors and their energy demand and CO_2 emissions. **For building clusters, these factors focus on street orientations, the layout of building clusters, over-shadowing between buildings, and the UHI effects**. For the transport sector, multinomial logistic regression analysis is applied in the option of modal splits from three aspects relating to:

- socioeconomic characteristics of the respondents, including gender, household income, and family car ownership;
- travel patterns of the respondents, which are travel modes, travel distance, frequency, purpose and travel time;
- and finally self-evaluation on travelling, including the condition of the travel

congestion, comfort level, and economical level

Earlier in this work, Chapter 2 has reviewed factors affecting carbon dioxide emissions from buildings and road transport. For issues relating to building energy demand, factors such as policies and urban forms are difficult to examine because the technical tools can only do the quantitative calculation, assessment, and analysis. This study examines energy consumption and carbon dioxide emissions related to factors shown in Table 7.1. **These factors are chosen based on the literature review at the community and urban scale**. Moreover, this research still attempts to develop deeper into a stricter discussion, by simulation and regression analysis, about the issues strongly related to the reduction of energy use and carbon dioxide emissions.

Table 7.1 The selected variables for quantitative analysis in this research

Sectors	Quantitative methods	Variables	Description
Building clusters	Simulation analysis	Street orientation	Four street orientations are analysed (0,45, 90,135)
		The layout of building clusters	Vertical and horizontal layouts for building clusters
		Over-shadowing	Open, normal, and dense situations between buildings
		Urban heat island effects	Ambient temperature changes within one degree
Travel mode choice	Regression analysis	Socioeconomic characteristics of respondents	Gender, household income, and vehicle ownership
		Travel patterns of the respondents	Travelled distance, time, frequency and travel purpose
		Self-evaluation on travelling	The conditions of the travel congestion, comfort level, and travel cost

7.2 Parametric analysis of a list of variables on building clusters

Before discussing the following parts, the overall urban geometry is illustrated first. A representative urban geometry is quite impossible to find if all parameters must be considered, including archetypal building form, the urban degree of compactness, street aspect ratio, and the orientation. For this reason, Martin and March (1972) introduce simplified archetypal building forms to limit the complexities found in real urban textures and to examine and compare the impact of geometry alone. In their study, they classify buildings into three basic types: The Slab or Street, the Pavilion or Tower, and the Court (Fig. 7.1). The Street or Slab extends, potentially, infinitely along one axis. The Pavilion or the Tower is finite on its plan form. The Court extends along two. Table 7.2 describes the basic elements for studying at the community scale in this research. For the building cluster analysis, the cooling and heating demand, and the solar gains are presented and analysed.

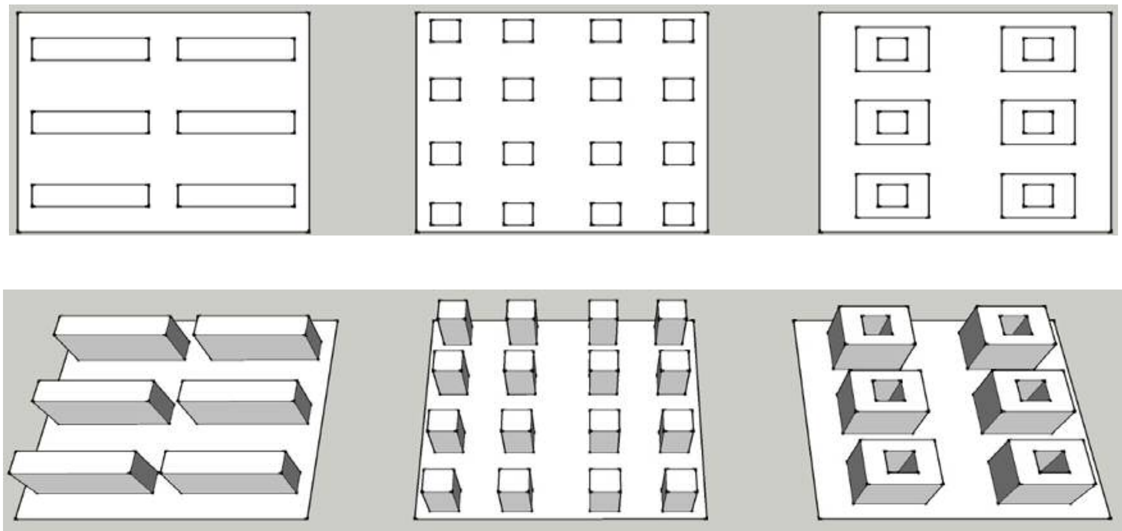
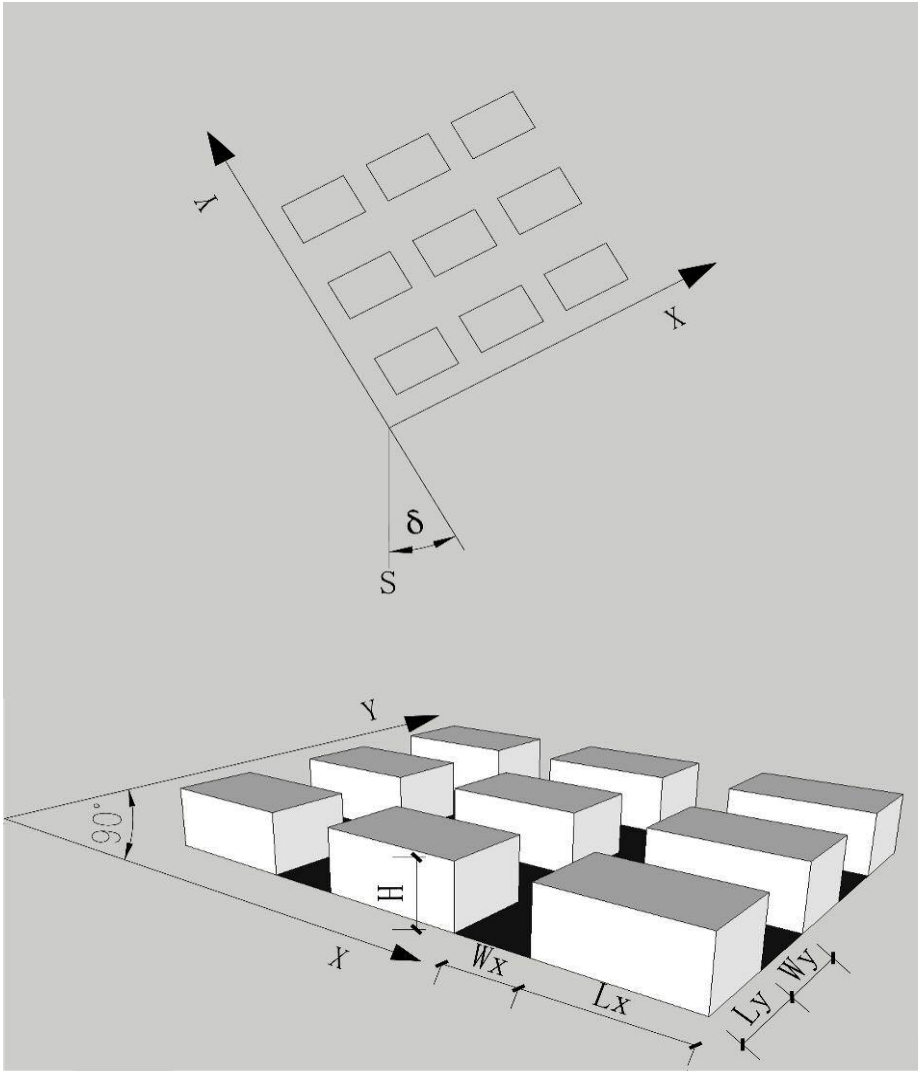


Figure 7.1 Three different built forms: slab or street, pavilion or tower, and court (from left to right)

Table 7.2 Basic elements of the built forms at the community scale

Street Scale	Type	
		The basic parameters of urban form: Block Azimuth (δ), Building height (H), building length (Lx) Building width (Ly), building distance along the X-axis (W_x) and the Y-axis (W_y)
	Indicators	Building storeys: n Building length, width, and height: Lx, Ly, H Depth ratio $l=L_x/L_y$ Building distance along X-axis: W_x Building distance along Y-axis: W_y Building relative displacement along X-axis: △x Building relative displacement along Y-axis: △y

7.2.1 Street orientation

Streets are significant parts of urban open spaces and have a significant role in creating urban microclimates. The street orientation influences the amount of solar radiation received by the street surfaces and also airflow in urban canyons. The urban streets vary in geometry, as defined by the ratios of height to width, length to width, and the orientation that is defined by a long axis (Shishegar 2013). These parameters directly influence the absorption and emission of solar radiation.

This study uses the slab-built form as the basic form to analyse different variables on the energy performance of commercial building clusters, focusing on cooling and heating demand and solar gains. In order to compare how different street orientations affect the cooling, heating demand, and the solar gains of the building cluster, this work set only the orientation as the variable (δ=0; 45; 90;135), and other factors such as the floor area ratio, building density, storeys, height as constant. The parameters are set in Table 7.3. Then Figure 7.2 sets four different street orientations, from 0 degrees to 135 degrees, split by 45-degree interval.

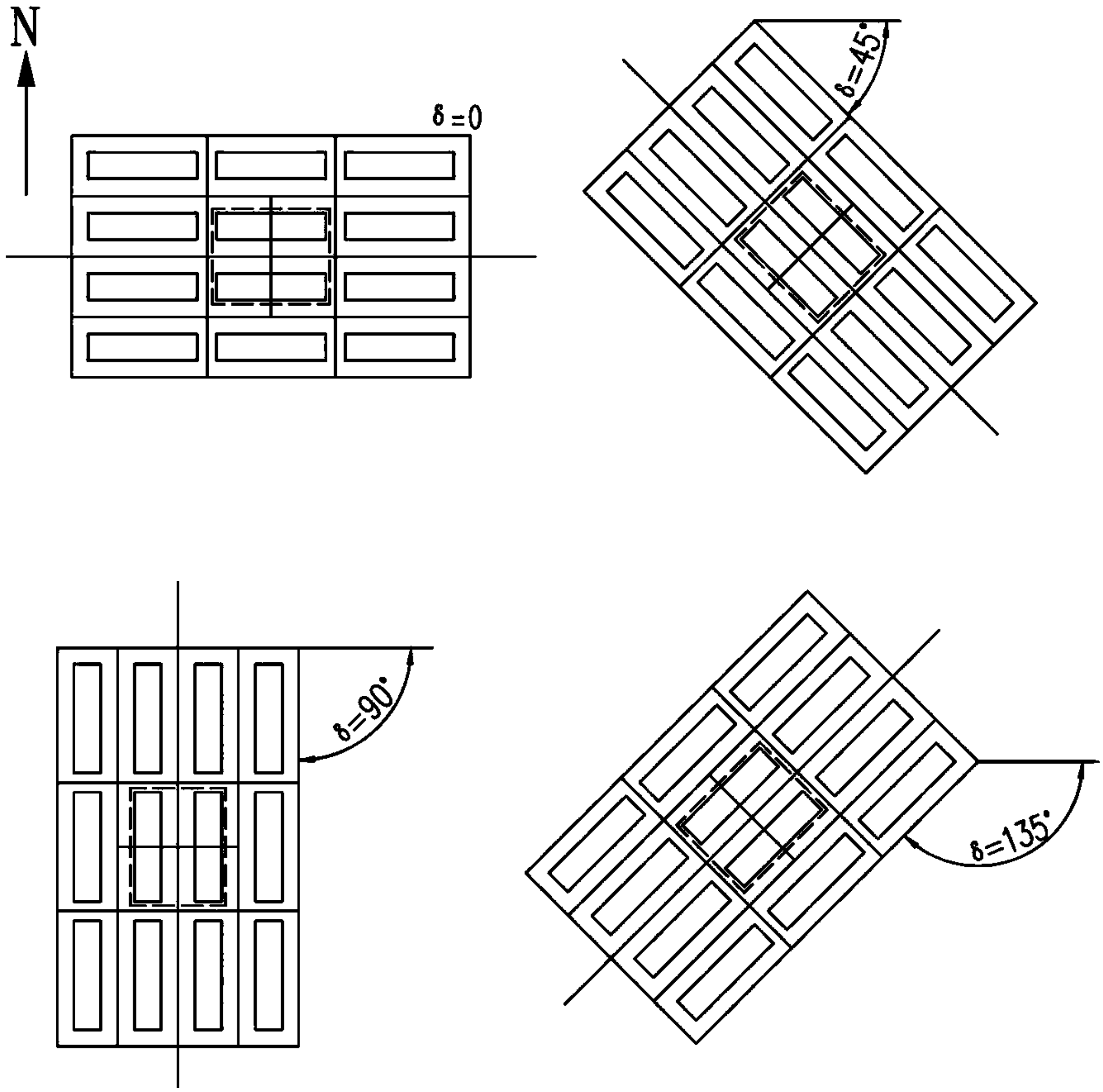


Figure 7.2 Four street orientations (Block Azimuth (δ)) change from 0 to 135 degrees (45degrees intervals)

Table 7.3 Parameters setting for street orientation alteration

Slab	Floor area ratio	building density	Floor areas（m^2）	Building height (m)	Storeys
	3.93	0.33	259,200	36	12
Case 1	δ=0		259,200	36	12
Case2	δ=45		259,200	36	12
Case 3	δ=90		259,200	36	12
Case 4	δ=135		259,200	36	12

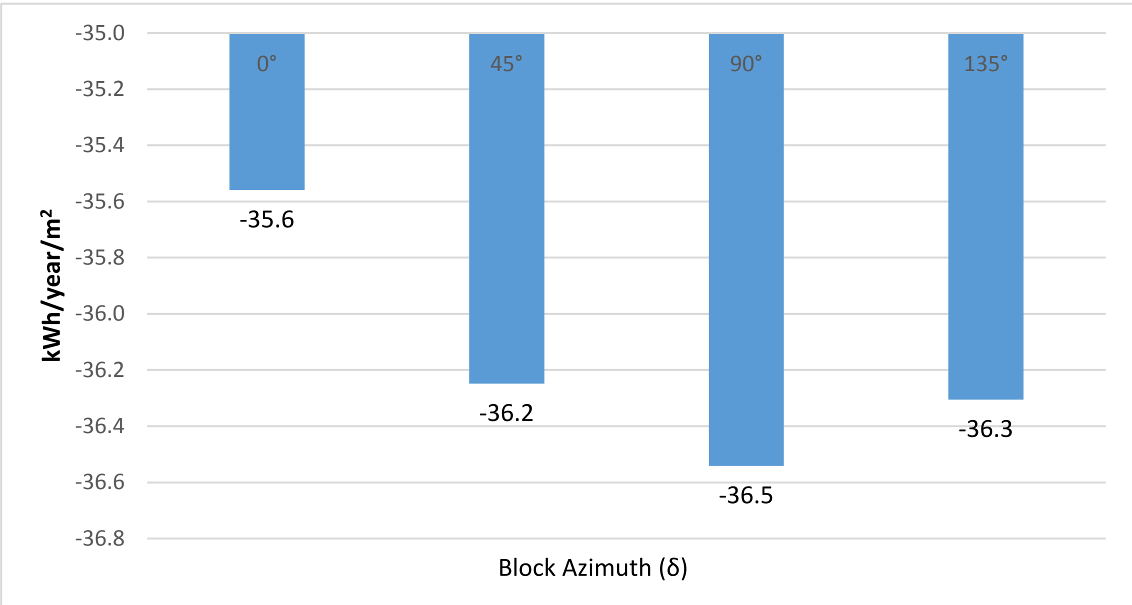


Figure 7.3 Cooling demand for four street orientations

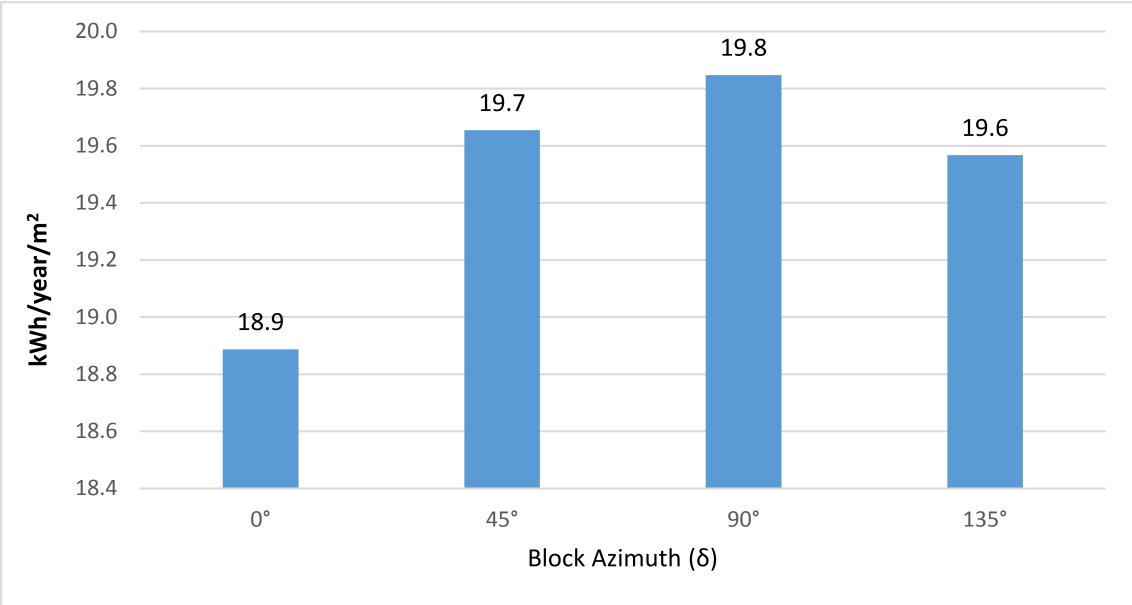


Figure 7.4 Heating demand for four street orientations

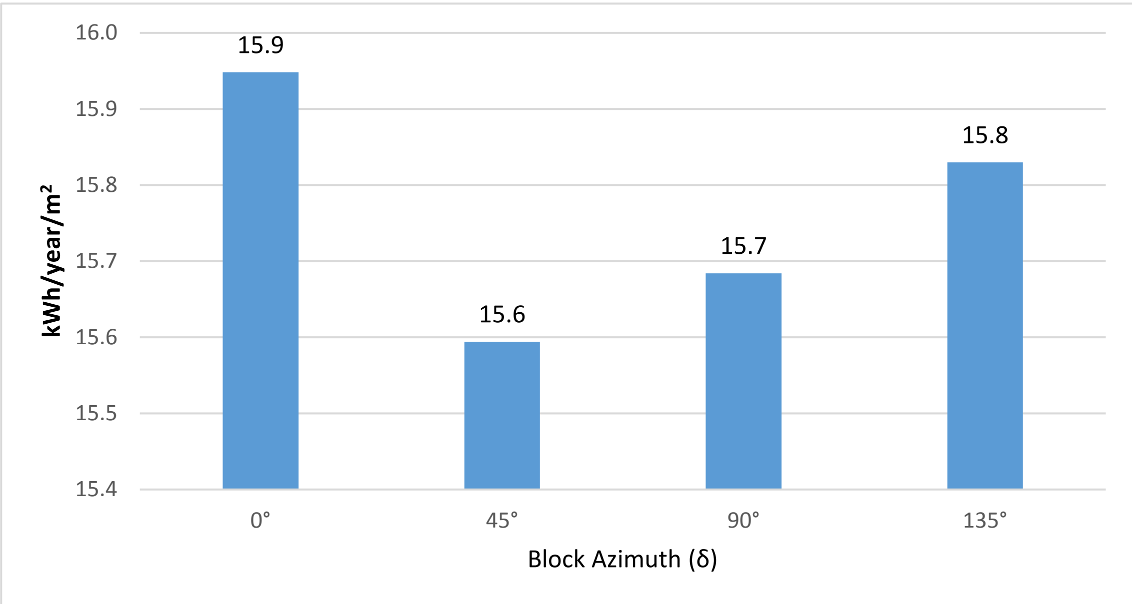


Figure 7.5 Annual solar gains per square metre for different street orientations

Figure 7.3 and Figure 7.4 present the effect of street orientations on heating and cooling demand, and solar gains are also analysed with four different street orientations in Fig. 7.5. The results show that the energy demand for heating and cooling is totally different, as well as the solar gains. From the four different orientations, the following conclusions can be drawn. Firstly, there is the least energy demand for building clusters on the N-S orientation (δ=0), standing at around 54.5 kWh/m^2/year (cooling demand plus heating demand). Moreover, the cooling demand was almost double the heating demand for all the cases, almost 36 kWh/ m^2/year vs.18 kWh/ m^2/year. Secondly, for the street orientation of 45-degrees and 135-degrees, the heating demand was almost the same, as well as the cooling demand, but in different values. Thirdly, buildings on E-W orientation (δ=90) has the highest energy, with around 56.3 kWh/ m^2/year out of these four different orientations, and this indicates that this orientation is the worst one among them for energy-saving.

Figure 7.5 illustrates that solar gains vary in the different street orientations. Figure 7.3 and Figure 7.4 describe why buildings on N-S orientation (δ=0) have the least energy demand, and the cooling demand is greater than the heating demand. The results can be explained by the fact that among these four orientations, the highest solar gains from the buildings are for those buildings in the N-S orientation. In the winter, those solar gains contribute to positive effects for heating, while in the summer, the gains lead to the adverse effects on the cooling demand, which means a larger energy demand needed to cool these extra gains. Therefore, the cooling demand is greater than the heating demand.

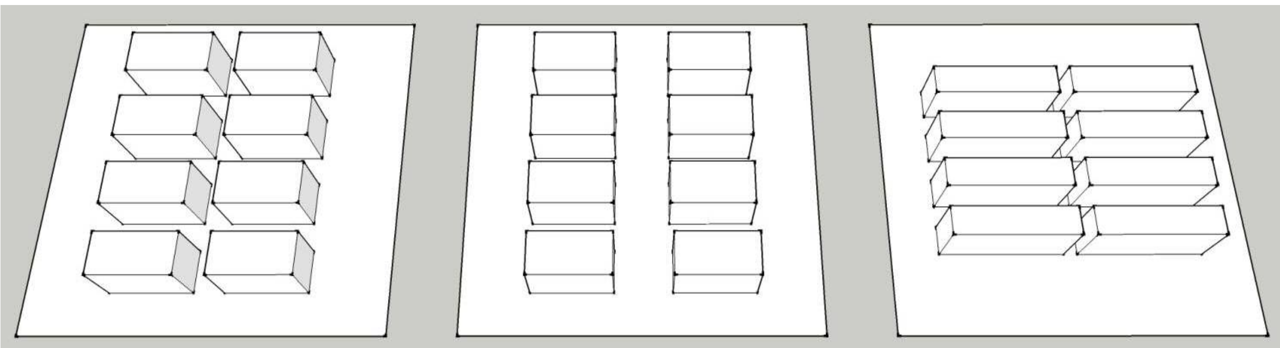
The above analysis indicates that the orientation of building clusters has proved that it is critical for the heating and cooling demand. Based on the modelling commercial prototype for this analysis, if the long axis of buildings faces the south-north, then the building would consume far less energy during the summer time. However, energy demand is determined by many factors when a group of buildings exists, which all affect each other. For example, the effect of over-shadowing from other buildings can block the accessibility of light, as well as the wind directions. Consequently, to explore the best street orientation for building clusters, a group of factors should be considered together in order to balance their effects, and these points are crucial, especially in the Master Planning stage.

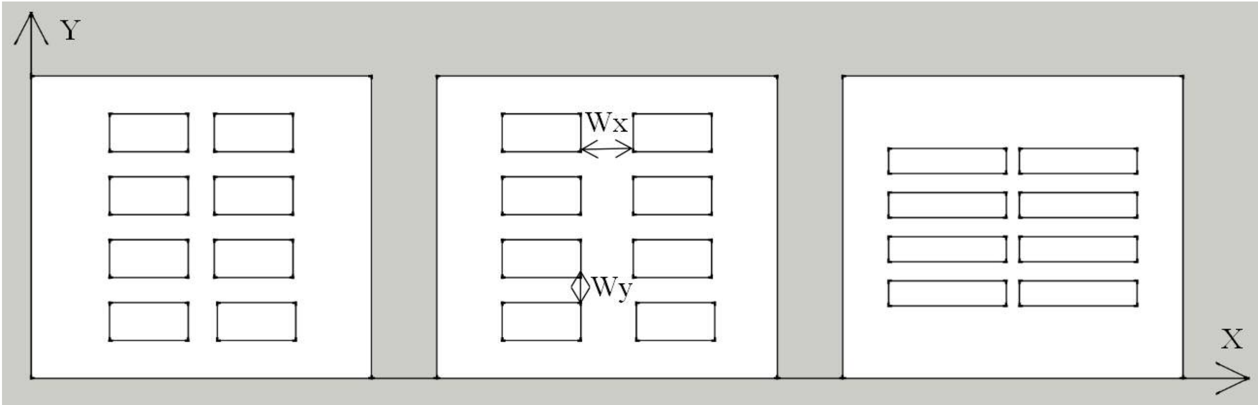
7.2.2 The layout of building clusters

The layout of building clusters focuses on two aspects: horizontal layout (Wy/Wx, △X/Wx, △Y/Wy) and vertical layout (△H). The details are presented in the following parts.

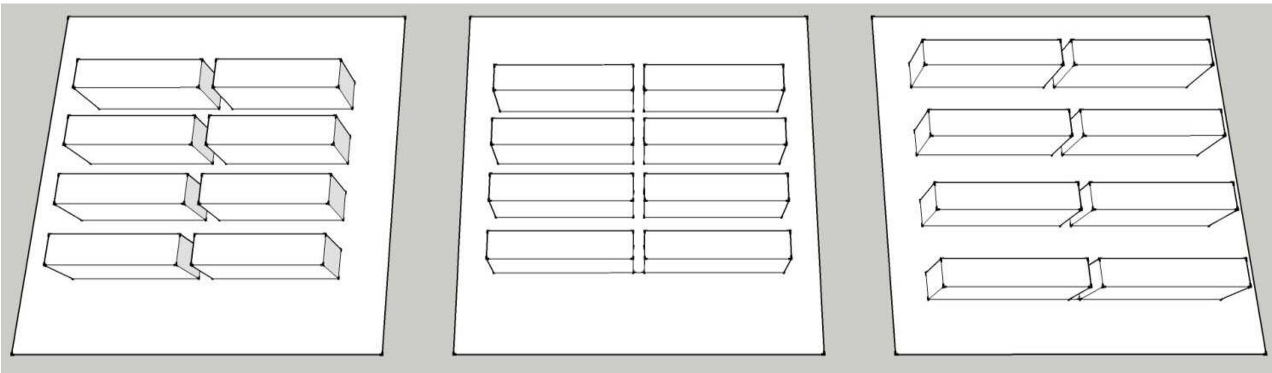
1) Horizontal layout (Wy/Wx)

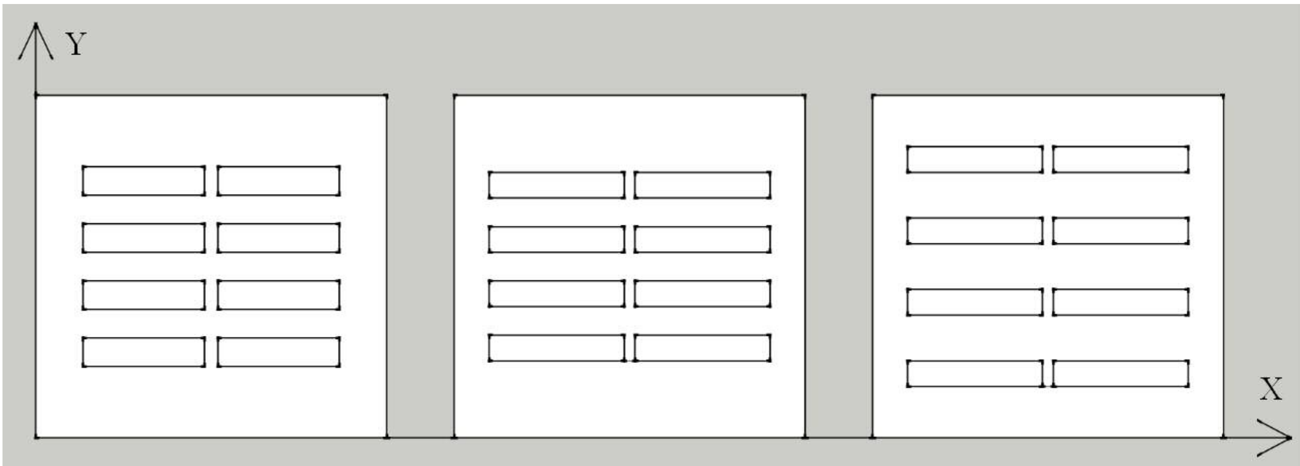
For the horizontal layout study, firstly, this work examines the alterations of the ratio Wy to Wx, from 0.5 to 4, which are 0.5, 1, 1.5, 2, 2.5, and 4. Other variables, such as building cluster density, floor area ratio, building storeys, and their heights, remain constant. The indicator (Wy/Wx) is used to measure how this alteration affects energy consumption of the building cluster.





Case1: Wy/Wx=1 Case2: Wy/Wx=0.5 Case3: Wy/Wx=1.5





Case4: Wy/Wx=2 Case5: Wy/Wx=2.5 Case6: Wy/Wx=4

Figure 7.6 Horizontal layout alteration: Wy/Wx from 0.5 to 4 (from left to right)

Table 7.4 Variables setting for Wy/Wx

Case	Building density	Floor area (m^2)	Floor area ratio	Building storey and Height (m)	Wy (m)	Wx(m)	Wy/Wx
1	0.23	172800	2.77	12 /3m	20	20	1
2	0.23	172800	2.77	12 /3m	20	40	0.5
3	0.23	172800	2.77	12 /3m	15	10	1.5
4	0.23	172800	2.77	12 /3m	20	10	2
5	0.23	172800	2.77	12 /3m	20	8	2.5
6	0.23	172800	2.77	12 /3m	32	8	4

Figure 7.6 is the visualisation of the horizontal layout Wy/Wx alteration from one to four, and more specific parameter settings can be found in Table 7.4. All the variables, such as building density, floor area, floor area ratio, remain constant, apart from the indicator of Wy/Wx. It is clear that how heating and cooling demand from buildings changes with the ratio of Wy to Wx.

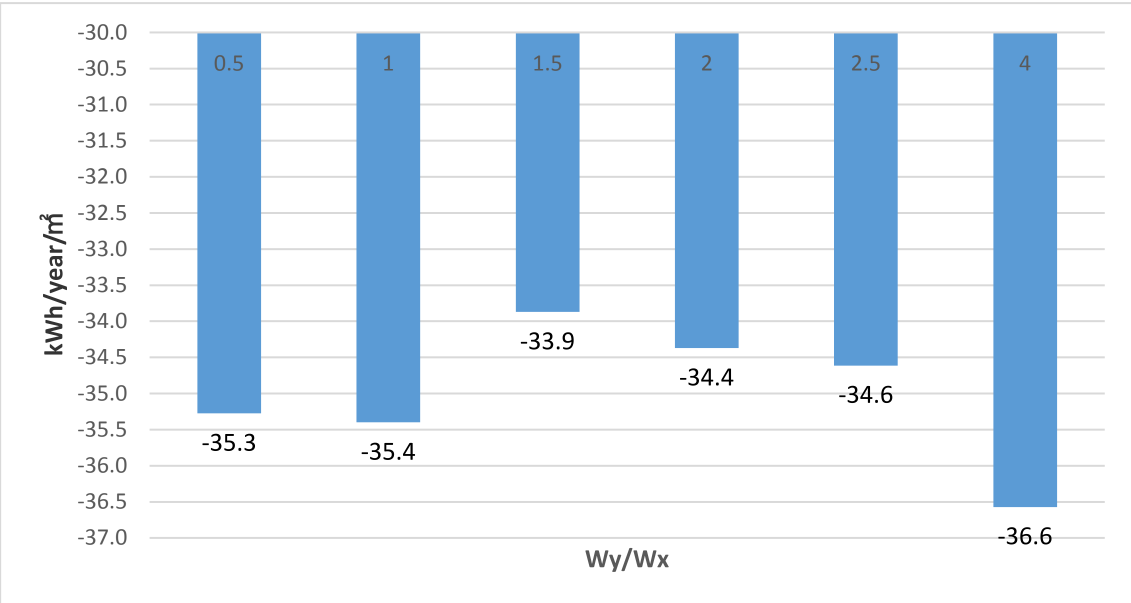


Figure 7.7 Cooling demand for the horizontal layout Wy/Wx alteration

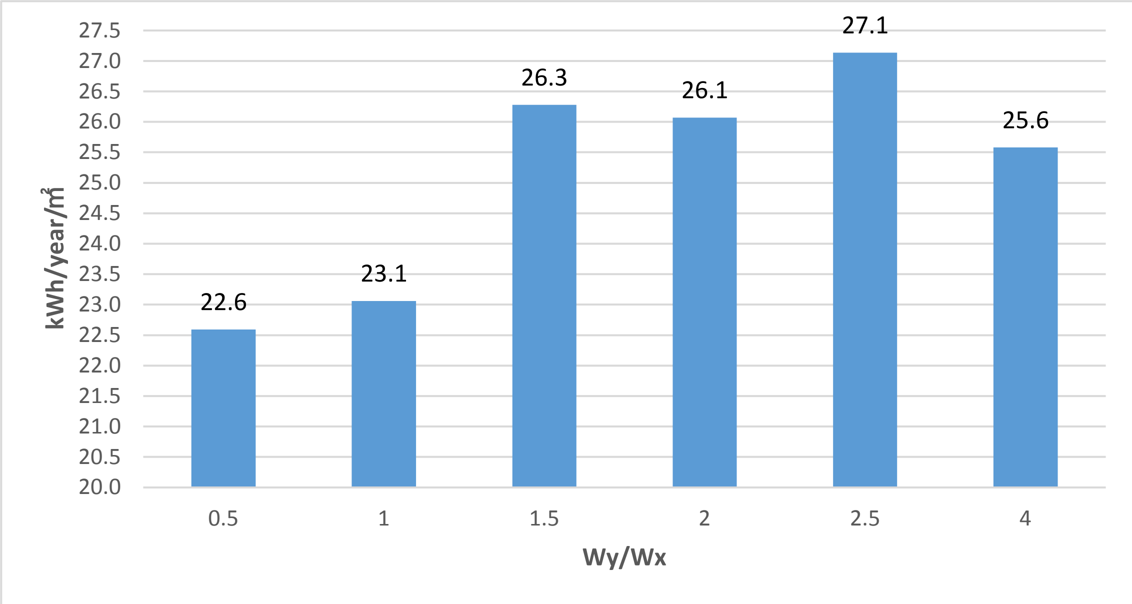


Figure 7.8 Heating demand for the horizontal layout Wy/Wx alteration

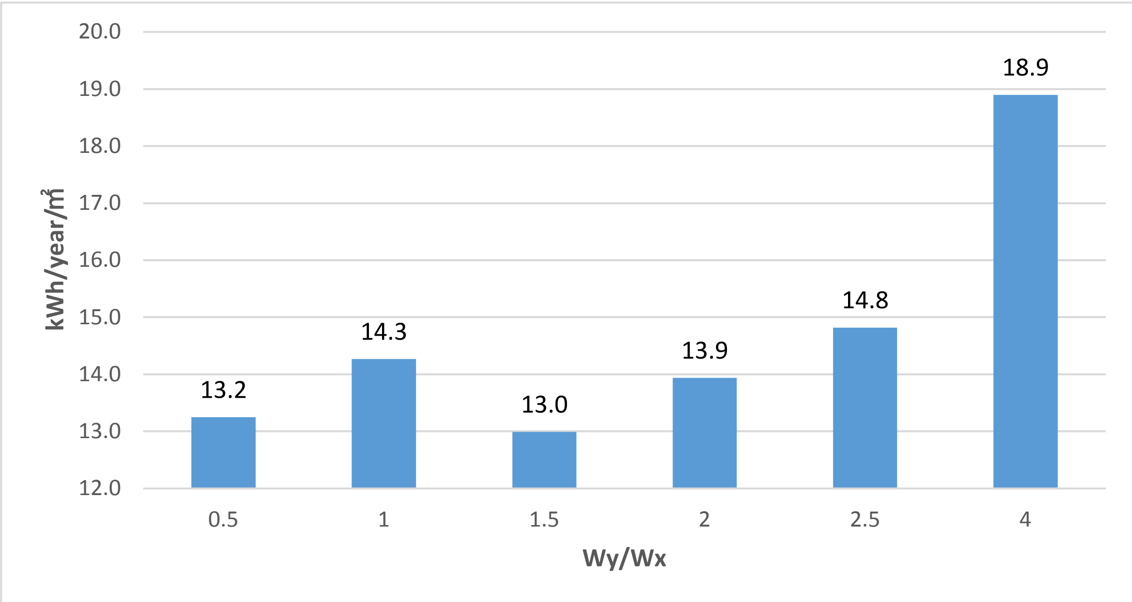
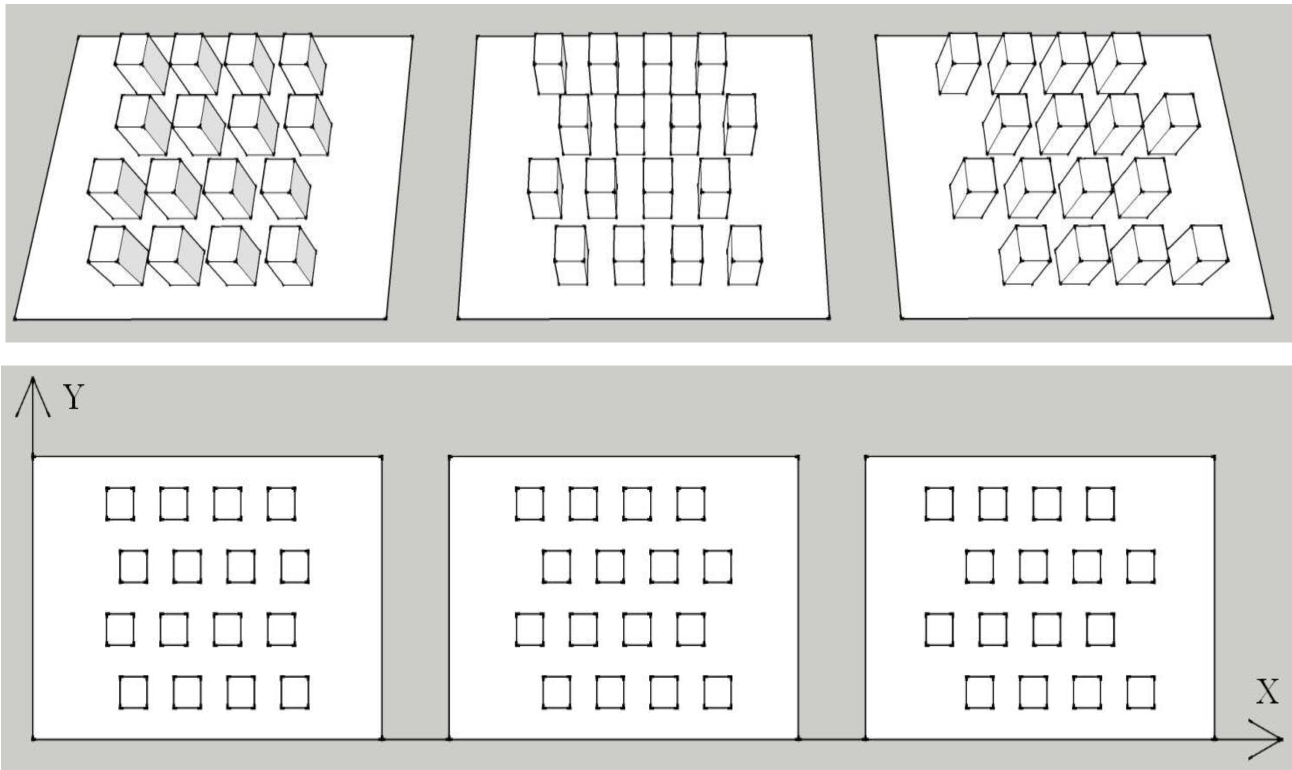


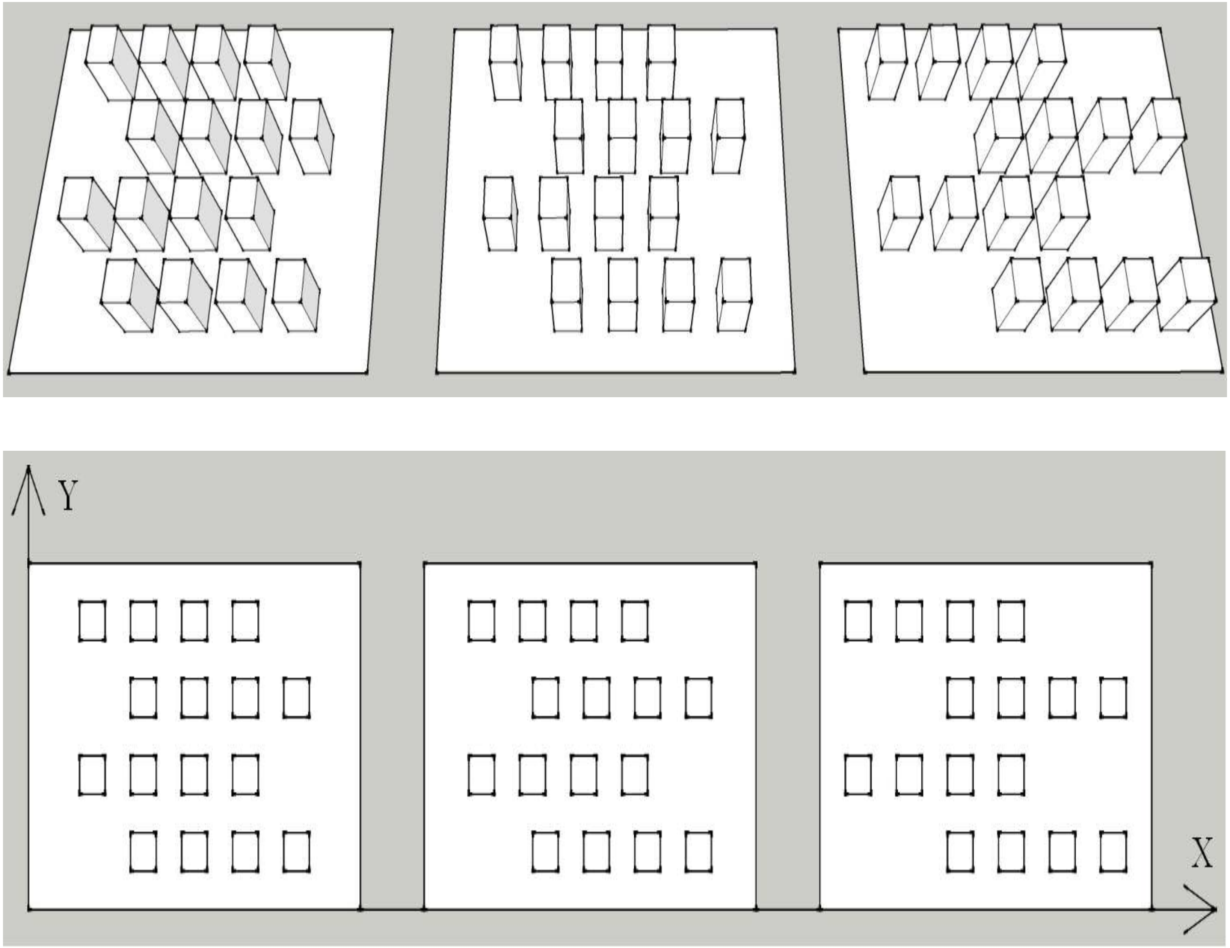
Figure 7.9 Annual solar gains for the horizontal layout Wy/Wx alteration

Figure 7.7, 7.8, and Figure 7.9 illustrate the annual cooling and heating demand, and the solar gains for building clusters, respectively. For the annual cooling energy consumption (Fig. 7.7), the highest value is required when the ratio of Wy to Wx is quite small (0.5 or 1) or very large (4). While for the heating demand, the relationship between the heating demand and the ratio of Wy to Wx is ambiguous. It seems that the larger the ratio, the greater the heating demand needed. For the overall energy demand, there is a positive effect on the ratio of Wy to Wx. As for the solar gains, they increased the ratio of Wy to Wx, from 1.5 to 4. The largest solar gains for building clusters are the ratio of 4 (Fig. 7.9), which is larger than any other conditions.

2) Horizontal layout (ΔX/Wx)



Case1: Δ x/Wx=0.5 Case2: Δ x/Wx=1 Case3: Δ x/Wx=1.5



Case4: Δ x/Wx=2 Case5: Δ x/Wx=2.5 Case6: Δ x/Wx=4

Figure 7.10 Horizontal layout alteration: ΔX/Wx

Table 7.5 Parameters conditions for horizontal layout alteration: ΔX/Wx

Case	Building density	Floor area (m^2)	Floor area ratio	Building storey and Height (m)	ΔX	Wx	ΔX/Wx
1	0.14	76800	1.64	12 /3m	10	20	0.5
2	0.14	76800	1.64	12 /3m	20	20	1
3	0.14	76800	1.64	12 /3m	30	20	1.5
4	0.14	76800	1.64	12 /3m	40	20	2
5	0.14	76800	1.64	12 /3m	50	20	2.5
6	0.14	76800	1.64	12 /3m	80	20	4

This section analyses the impact of the factor (Δx/Wx) on the energy demand. The visualisation of Δx/Wx can be seen in Fig. 7.10. The variable details can be seen in Table 7.5.

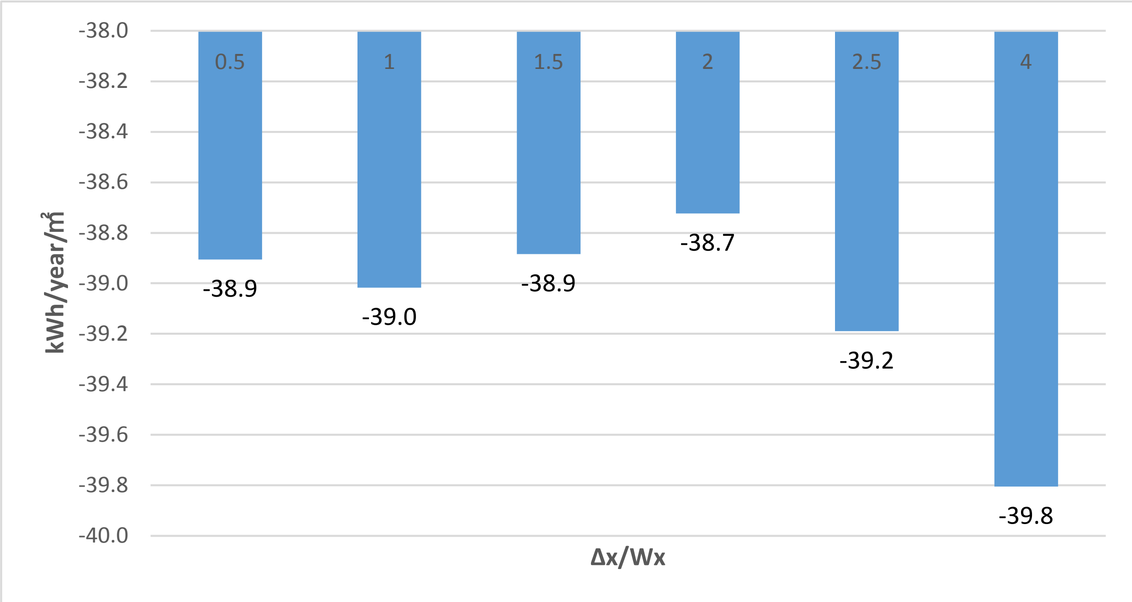


Figure 7.11 Cooling demand for the horizontal layout ΔX/Wx alteration

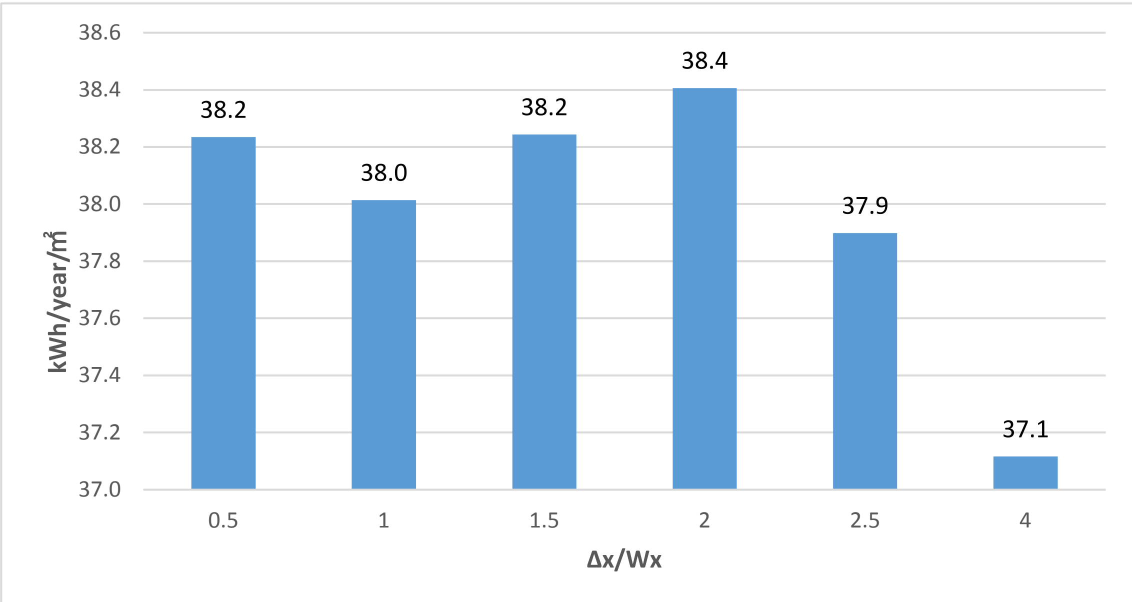


Figure 7.12 Heating demand for the horizontal layout ΔX/Wx alteration

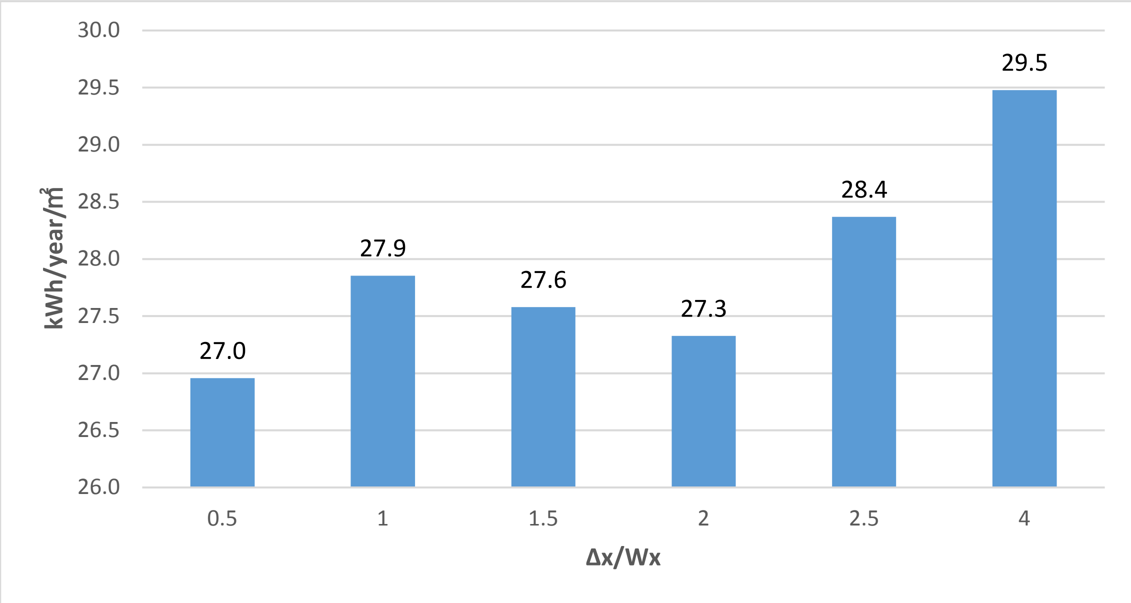
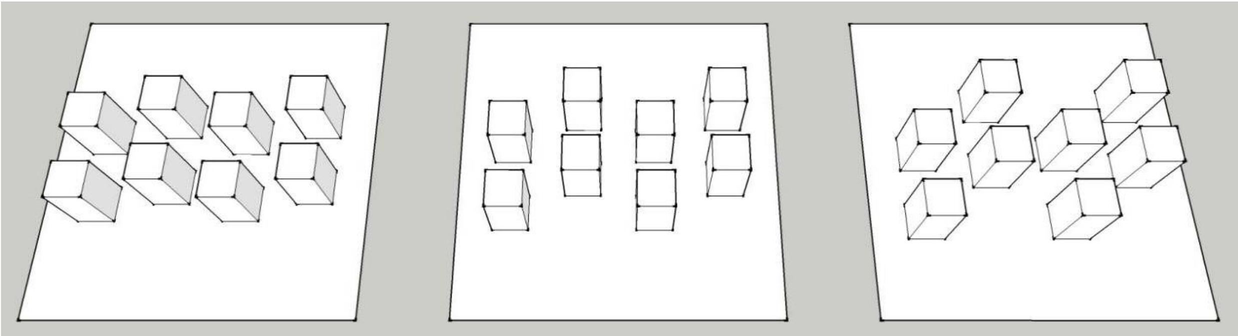
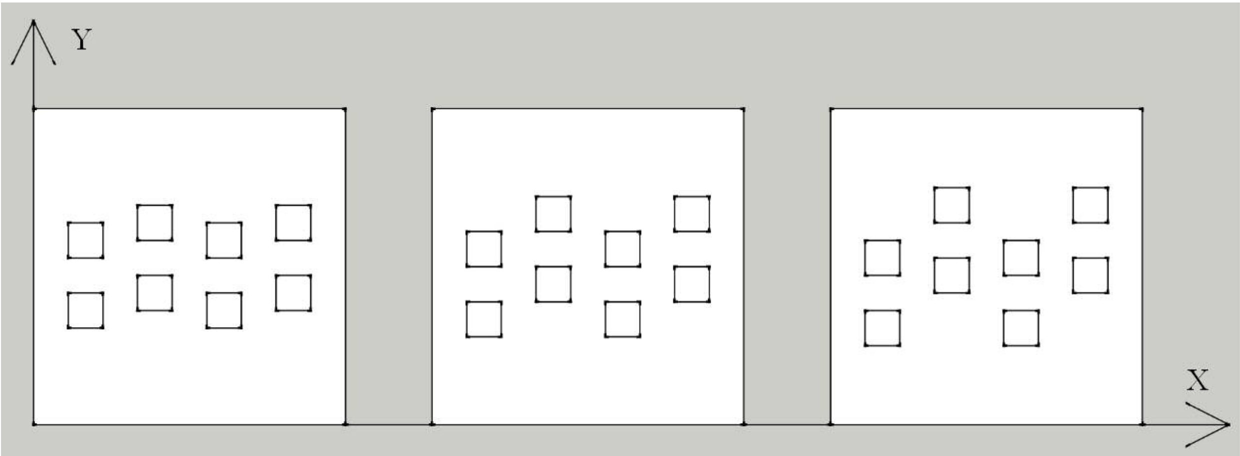


Figure 7.13 Annual solar gains for the horizontal layout Δx/Wx alteration

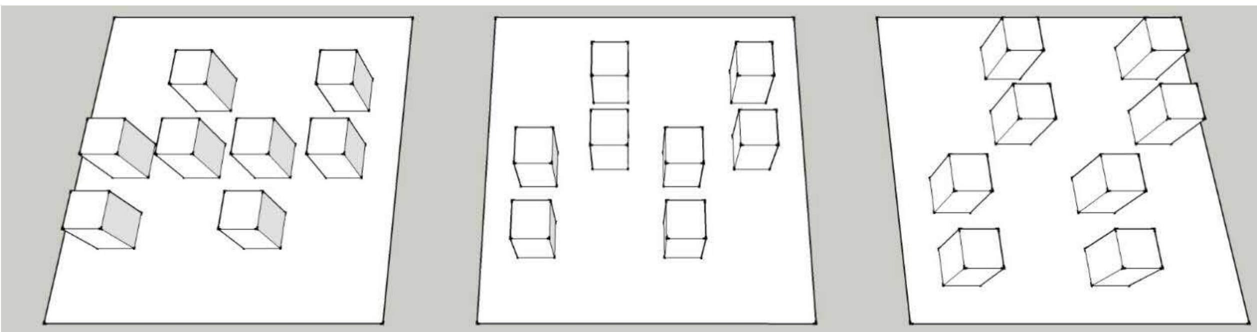
Figure 7.11, 7.12 and Figure 7.13 describe the simulation result. Energy demand in cooling and heating is reflected in Fig. 7.11 and 7.12. According to these two graphs, firstly, both the heating and cooling demands fluctuate. The highest cooling demand occurred when the ratio of Δ x to Wx was four. However, the same ratio was the lowest for heating demand. In fact, this indirectly validates that the simulated results are accurate since the highest cooling demand means the lowest heating demand, which is as anyone would expect. However, for the total energy demand, it seems that there is a little impact on the ratio of Δ x to Wx since the total energy demand either did not change with the ratio of Δ x to Wx, or there were only very small fluctuations. As for the solar gains, the highest value was in the ratio of four (Δ x/Wx), and there is no obvious relationship between the solar gains and the factor (Δ x/Wx) according to these changes, but one feature can be confirmed—there is an opposite trend between the heating demand and solar gains. The more solar gains from the buildings, the lower heating demand from the building clusters.

3) Horizontal layout (ΔY/Wy)





Case1: Δ y/Wy=0.5 Case2: Δ y/Wy=1 Case3: Δ y/Wy=1.5



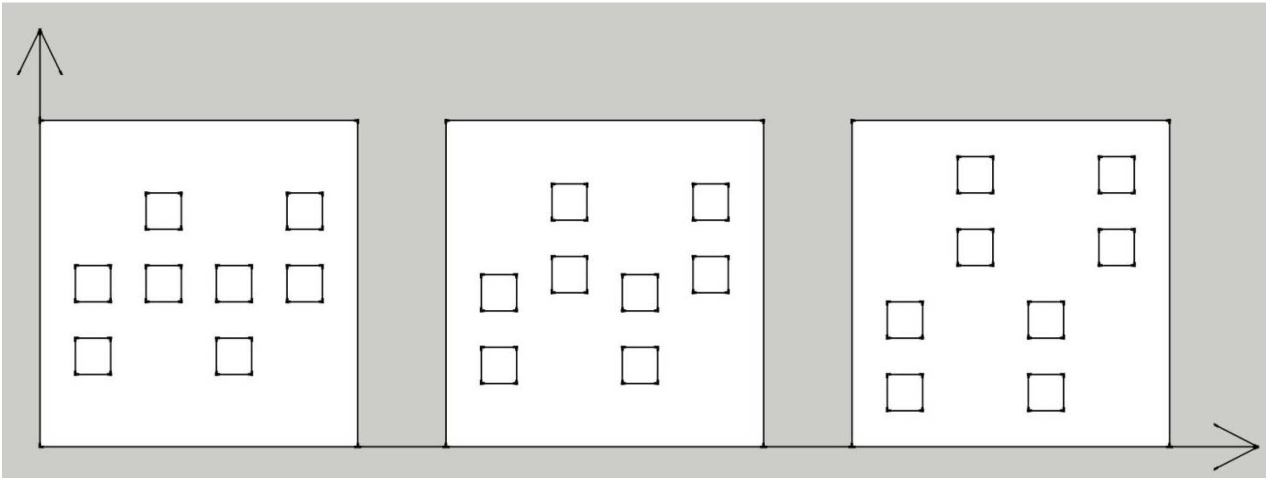


Figure 7.14 Horizontal layout alteration: Δy/Wy

Table 7.6 Parameters conditions for horizontal layout alteration Δy/Wy

Case	Building density	Floor area (m^2)	Floor area ratio	Building storey and Height (m)	Δy	Wy	Δy/Wy
1	0.10	38400	1.19	12 /3m	10	20	0.5
2	0.10	38400	1.19	12 /3m	20	20	1
3	0.10	38400	1.19	12 /3m	30	20	1.5
4	0.10	38400	1.19	12 /3m	40	20	2
5	0.14	76800	1.64	12 /3m	50	20	2.5
6	0.14	76800	1.64	12 /3m	80	20	4

The previous section has discussed the horizontal layout of Δ x/Wx changing with heating and cooling demand and the solar gains on buildings. In this section, the horizontal layout factor Δy/Wy is analysed with energy demand as well as their solar gains. Figure 7.14 is the visualisation of building clusters with different ratios of Δy to Wy, from 0.5 to 4. The detailed parameter information can be found in Table 7.6.

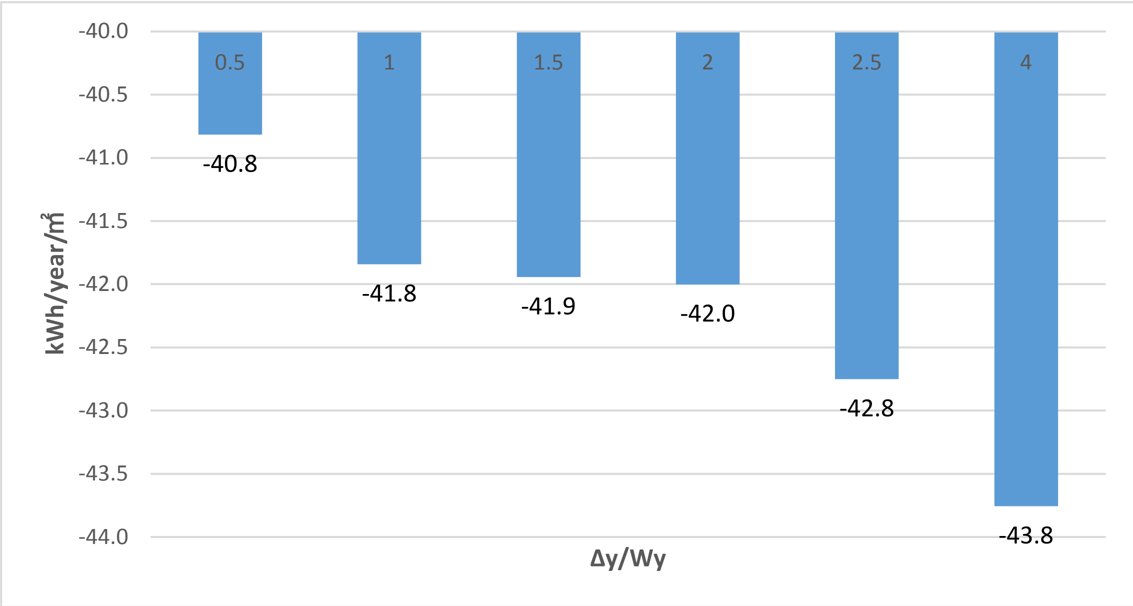


Figure 7.15 Cooling demand for the horizontal layout Δy/Wy alteration

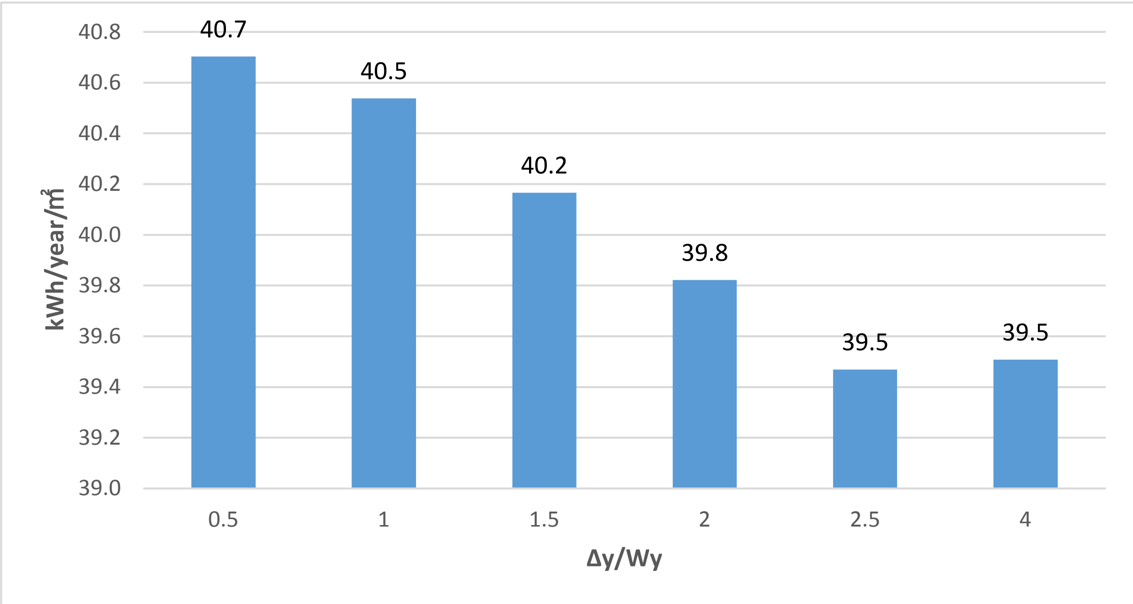


Figure 7.16 Heating demand for the horizontal layout Δy/Wy alteration

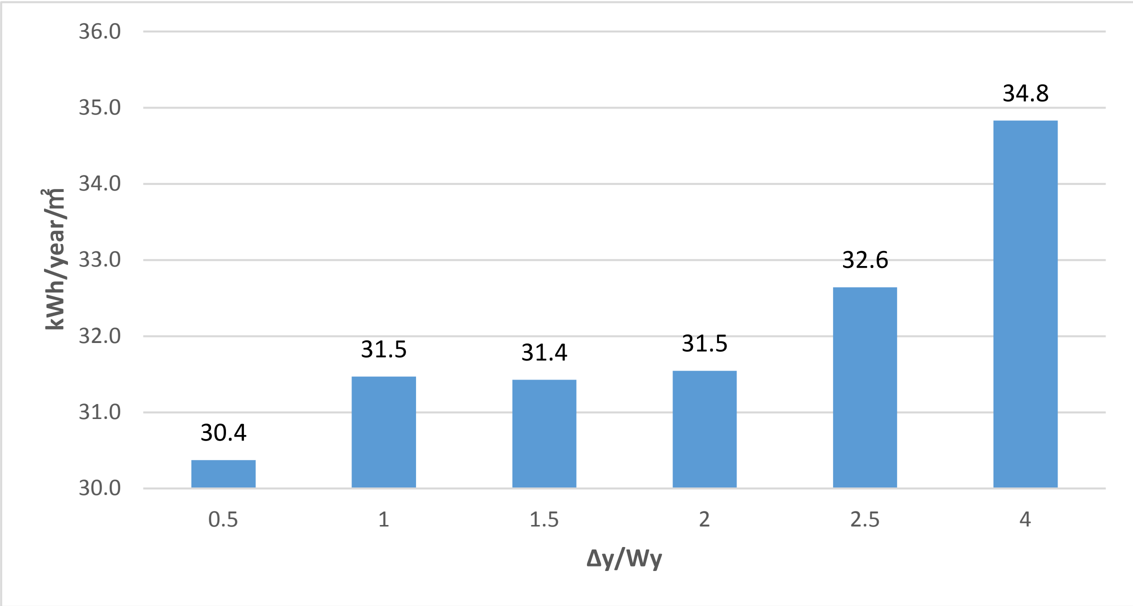
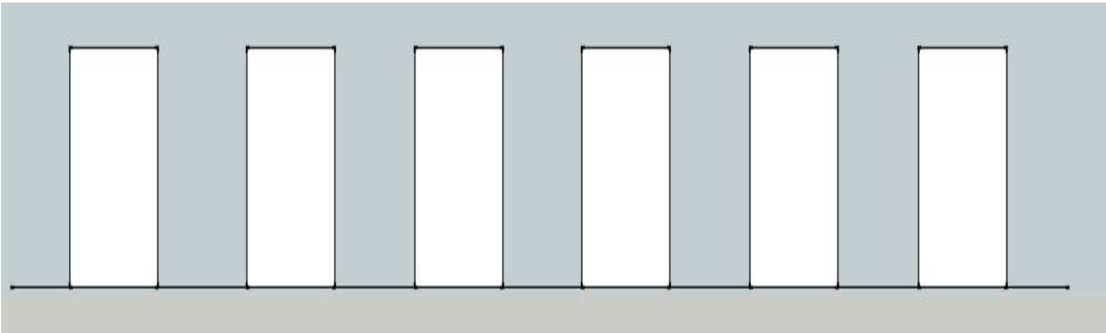


Figure 7.17 Annual solar gains for the horizontal layout Δy/Wy alteration

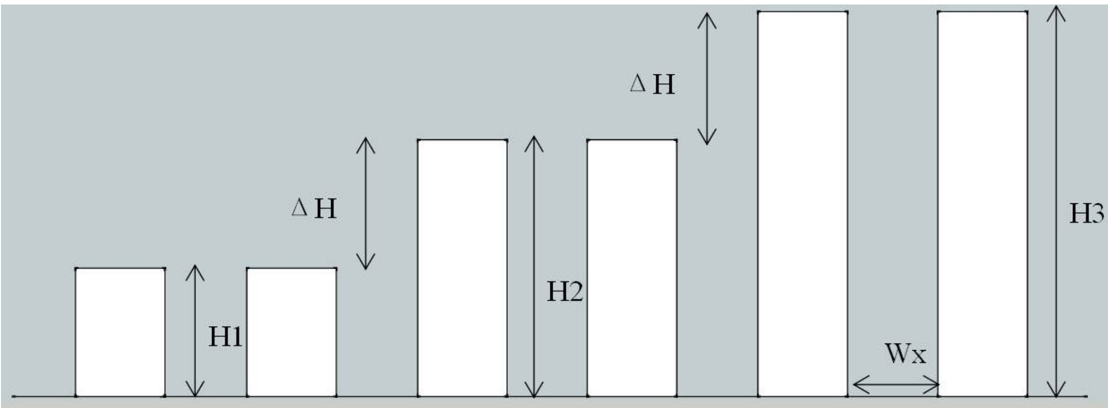
Figure 7.15 and Figure 7.16 reflect the correlation between energy demand and the variable Δy/Wy. It shows that the ratio of Δy to Wy has a positive effect on the cooling demand, while a negative effect for heating demand. The less the ratio has, the greater the heating demand requires. For the total energy demand, there is no obvious relationship with the ratio of △Y to Wy. When it comes to the solar gains (Fig. 7.17), it is evident that the larger the ratio, the greater the solar gains. This can be explained by the distance between buildings. The highest ratio represents the buildings being entirely exposed to each other without any shading, and this provides a greater chance for all buildings to obtain the solar gains for all buildings from different faces.

4) Vertical layout

Case 1 (Uniform building height H)



Case 2 (South-high and North-low)



Case 3 (South-low and North-high)

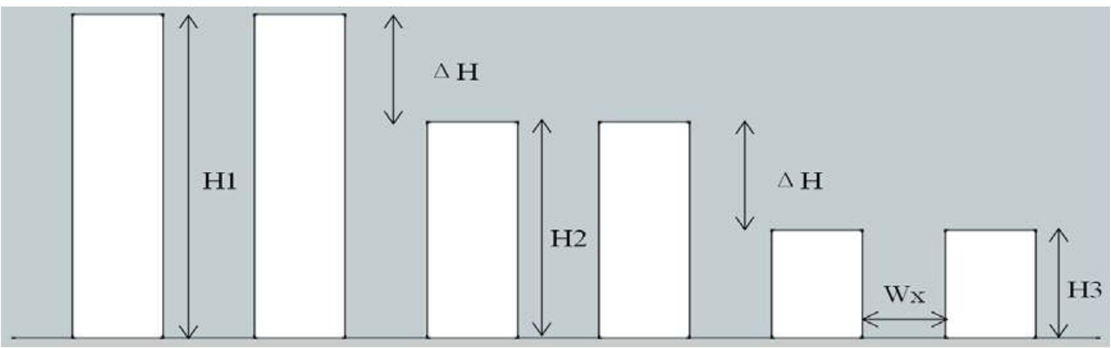


Figure 7.18 Vertical layout changes from south to north

Table 7.7 Parameters conditions on vertical layout changes with △H

Case	H_1 (m)	H_2 (m)	H_3 (m)	ΔH (m)	Wx (m)
1	72	72	72	0	20
2	36	72	108	36	20
3	108	72	36	36	20

Figure 7.18 describes the visualisation of different building heights and Table 7.7 provides conditions about the variables in three case conditions. All variables stay constant, save for the vertical height, and this is in order to analyse the impact of their height alteration on energy demand.

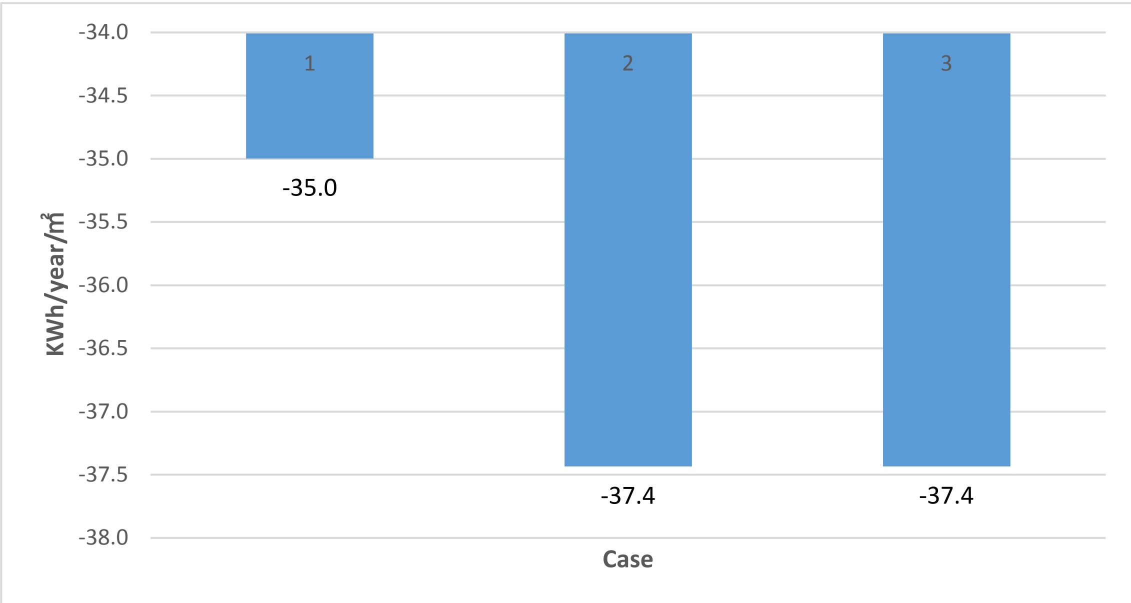


Figure 7.19 Cooling demand for the vertical layout ΔH alteration

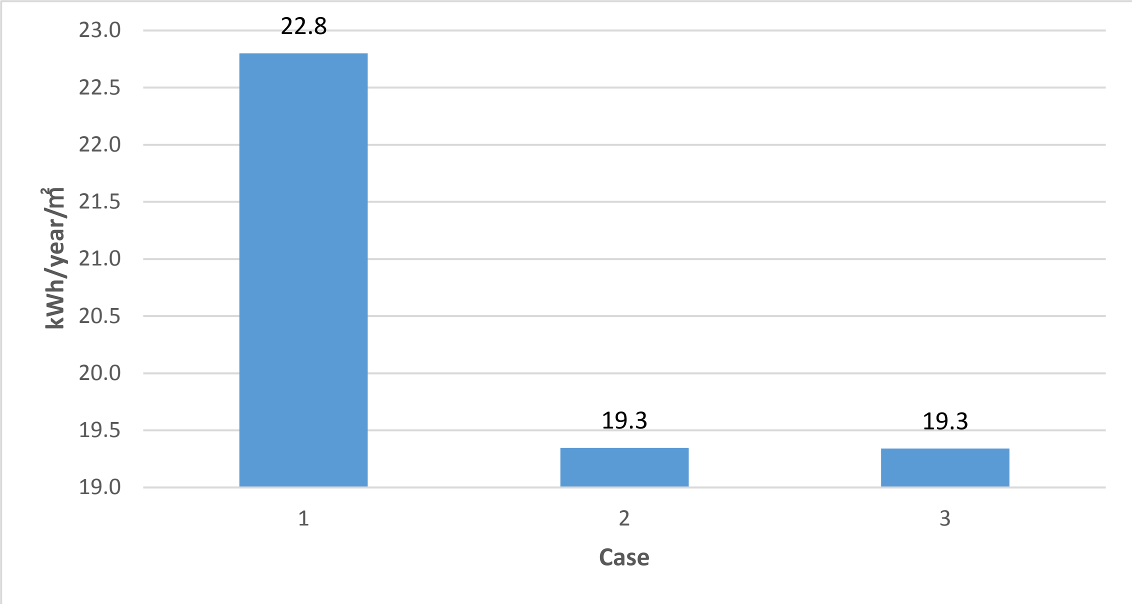


Figure 7.20 Heating demand for the vertical layout ⊿H alteration

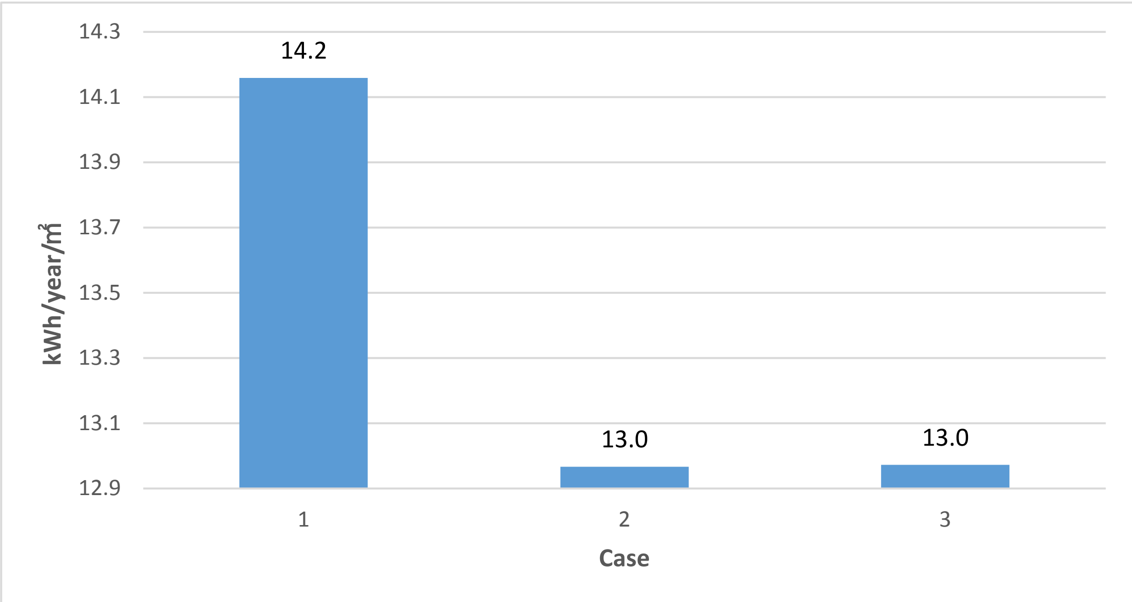


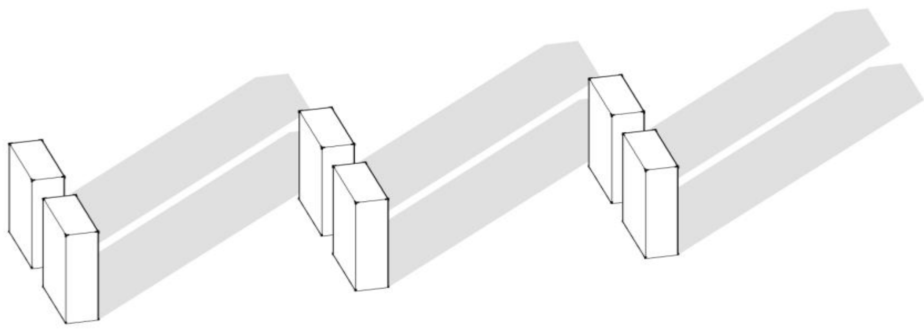
Figure 7.21 Annual solar gains for the horizontal layout △H alteration

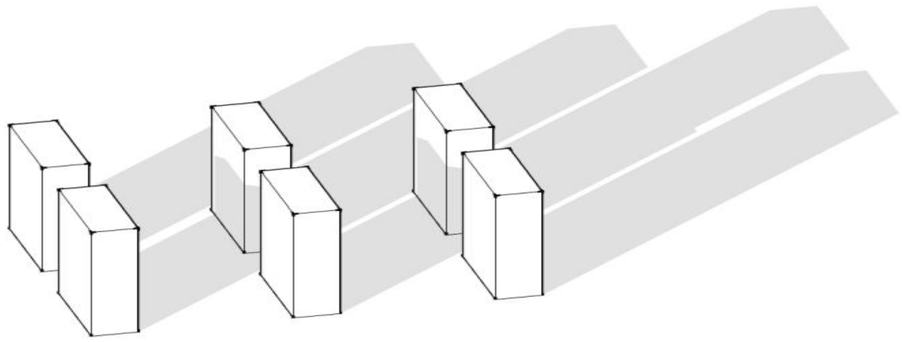
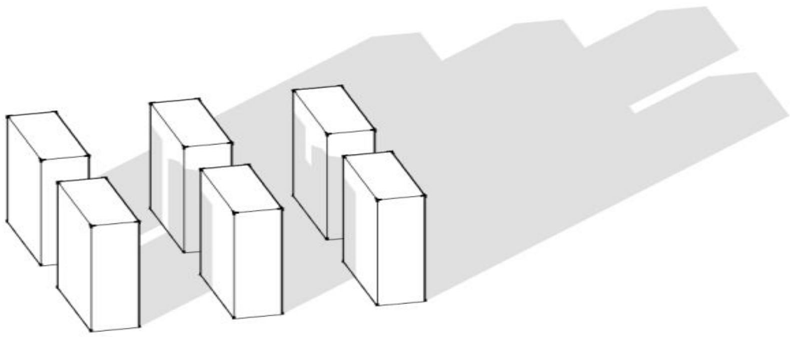
Figure 7.19 and Figure 7.20 show the cooling and heating demand among buildings, while Figure 7.21 describes the changes in solar gains with height differences. It found that the energy demand largely varies in building height as well as the solar gains. For the cooling demand, it requires 7% of more than the control group (uniform height: case 1), while the heating demand largely less than (15%) the control group. Overall, the total energy demand can be cut down by around 2% when there is a height difference between buildings. Meanwhile, building height difference can reduce 8% of solar gains compared to the uniform height of building clusters shown in Fig. 7.21.

7.2.3 Over-shadowing

There is no doubt that over-shadowing can reduce the energy demand by offering more shading for buildings, which indirectly leads to a reduction in cooling demand. Three cases are analysed, adopting the research of Jones et al. (2009) as the reference. The detailed conditions are described in Table 7.8.

Table 7.8 Parameters setting for overshadowing

Over-shadowing	Visual representation	Case
Open 20 storeys (60m) obstruction 120 m away		1

Normal 20 storeys (60m) obstruction 50 m away		2
Dense 20 storeys (60m) Obstruction 30 m away		3

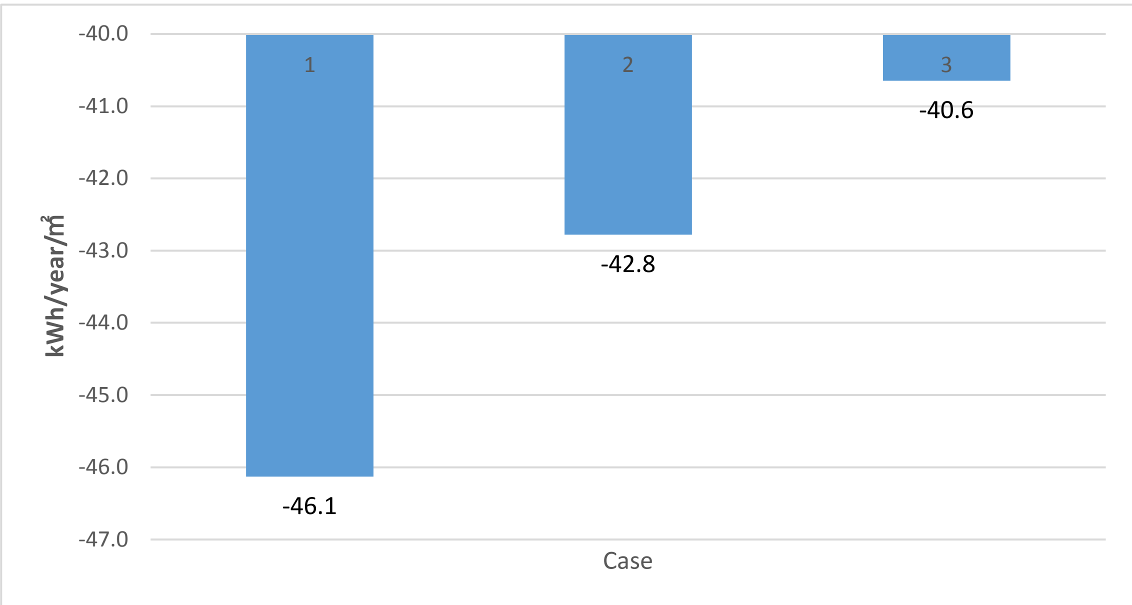


Figure 7.22 Cooling demand with over-shadowing alteration

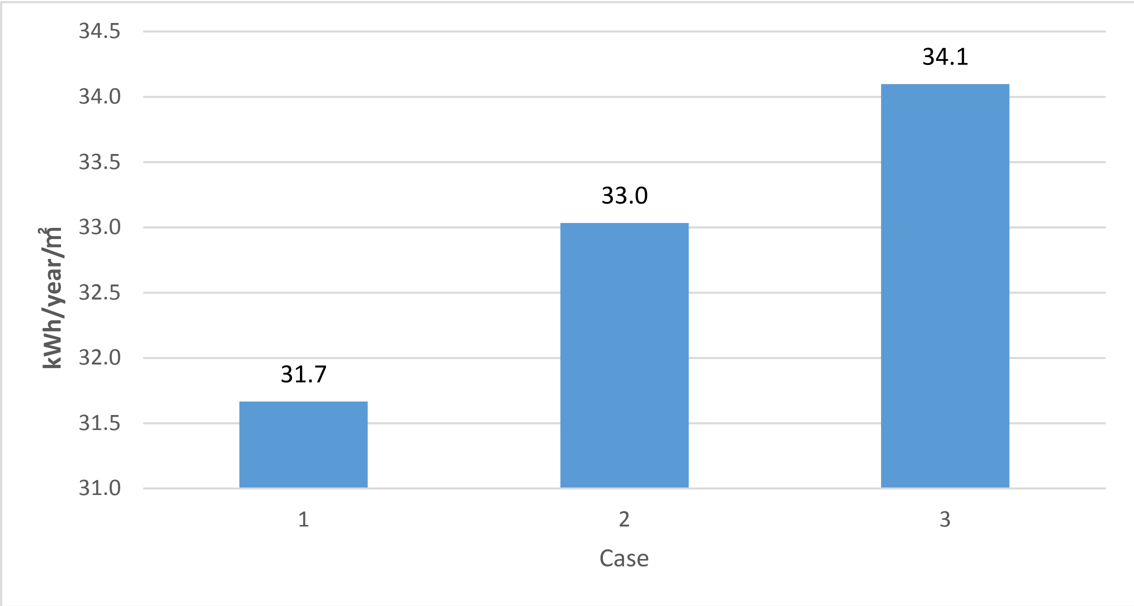


Figure 7.23 Heating demand with over-shadowing alteration

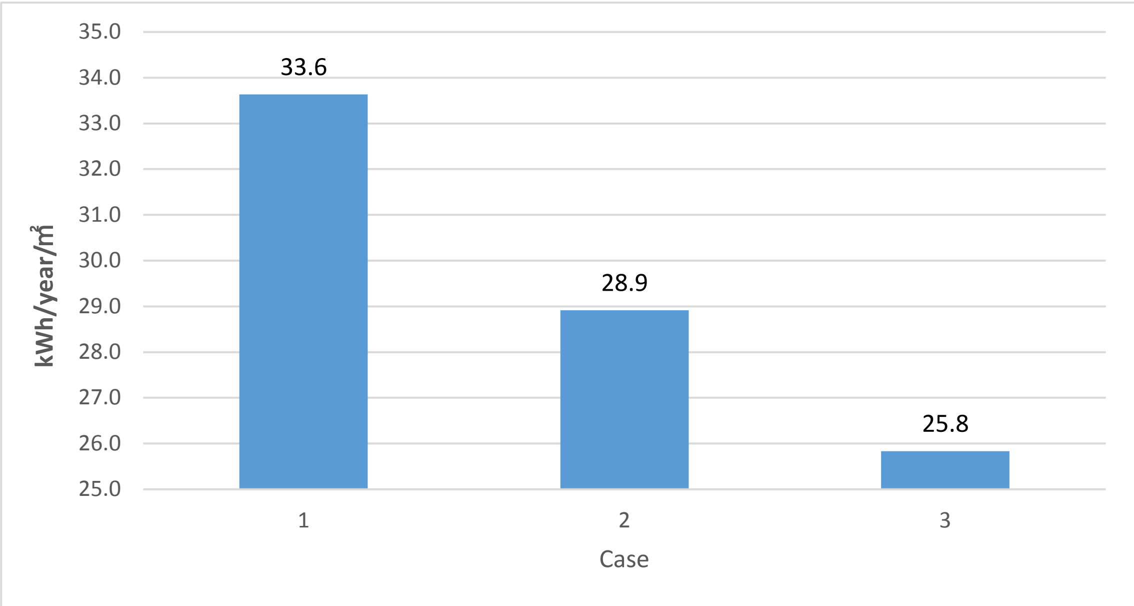


Figure 7.24 Annual solar gains with over-shadowing alteration

It becomes easier to recognise the impact of over-shadowing on energy demand from the results of the simulation with and without shading effects. Three cases of open, normal, and dense are analysed. According to Figure 7.24, annual solar gains in the open situation is 30% more than the dense situation, and this can be explained by the fact that buildings in dense areas provide shading for each other, thus reducing the heating demand but increase cooling demand as Fig. 7.22 and Fig. 7.23 illustrate. For the cooling demand, due to the shading effects offered by the surrounding buildings, it is less than 5% in the dense situations but increases by around 9% in the open situation compared with the normal level. As for the heating demand, it is less than 2% in the opening situation but greater than 5% in the dense situation compared with the normal level. Overall, for the total energy consumption, dense conditions can contribute to saving 4% of energy and 23% of reduction in solar gains compared to open conditions.

7.2.4 Urban heat island effects

The urban heat island (UHI) effects are the cumulative result of the urban impact leading to a rise in temperature within the built environment, resulting in "warm islands" within the city centre in comparison to rural environments (Corburn 2009; Zeng et al. 2010). The UHI phenomenon has been well-studied and is now an important planning consideration for urban sustainability (Lowry 1977; Nichol 2005). The rise in ambient temperature could have a potential impact on energy consumption in buildings, and the one-degree ambient temperature rise could result in an increase of electricity consumption by 9.2% and 3.0% in domestic and commercial sectors, respectively (Tarleton and Katz 1995). The main causes of the UHI phenomenon are due to the characteristics of urban construction and anthropogenic heat emissions. Urban surfaces usually consist of impermeable roads made from concrete and asphalt, which have a large thermal capacity and high thermal conductivity rates. As a result, these surfaces absorb solar radiation. Buildings absorb and store heat during daytime by absorbing shortwave radiation, and then release the heat into the atmosphere at night, increasing the ambient temperature (Bouyer et al. 2009). Li and Yu (2008) study the city heat environment in Wuhan deeply by the combinative method of Remote Sensing and CFD simulation. Based on their findings, the temperature distribution of Wuhan city is shown clearly in Fig. 7.25. Li and Yu point out that the temperature around the Yangtze River is relatively high, and the reason is the high building density beside the Yangtze River and the poor city ventilation.

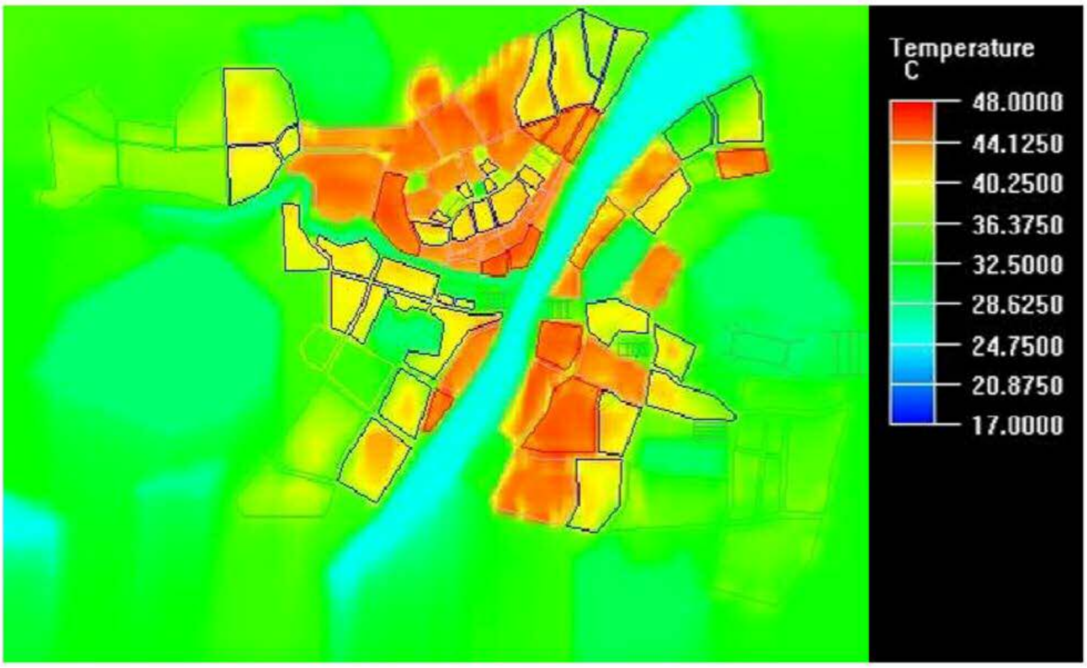


Figure 7.25 City heat environment simulation of Wuhan city in daytime
Source: Li and Yu (2008)

Many factors affect the urban heat island covering the climatic variations (clear sky, partially cloudy and cloudy periods), geographical variation (core city, semi-city and rural areas) and on-site variables such as the ambient temperature, ventilation and wind direction. However, the relationship between the ambient temperature and UHI is quite complicated due to the uncertainty of the space and time. This study assumes that the temperature changes linearly with the time to simplify the model. Three cases are studied within UHI effect on energy demand by an increase or decrease of 1℃ in the ambient temperature compared to the standard model in which the ambient temperature remains constant.

Table 7.9 Parameters setting for ambient temperature changes with 1 ℃

Case	Temperature change	Wx (m)	Wy (m)	Building Height (m)	Building storey
1	Increase 1℃	60	30	36	12
2	Constant	60	30	36	12
3	Decrease 1℃	60	30	36	12

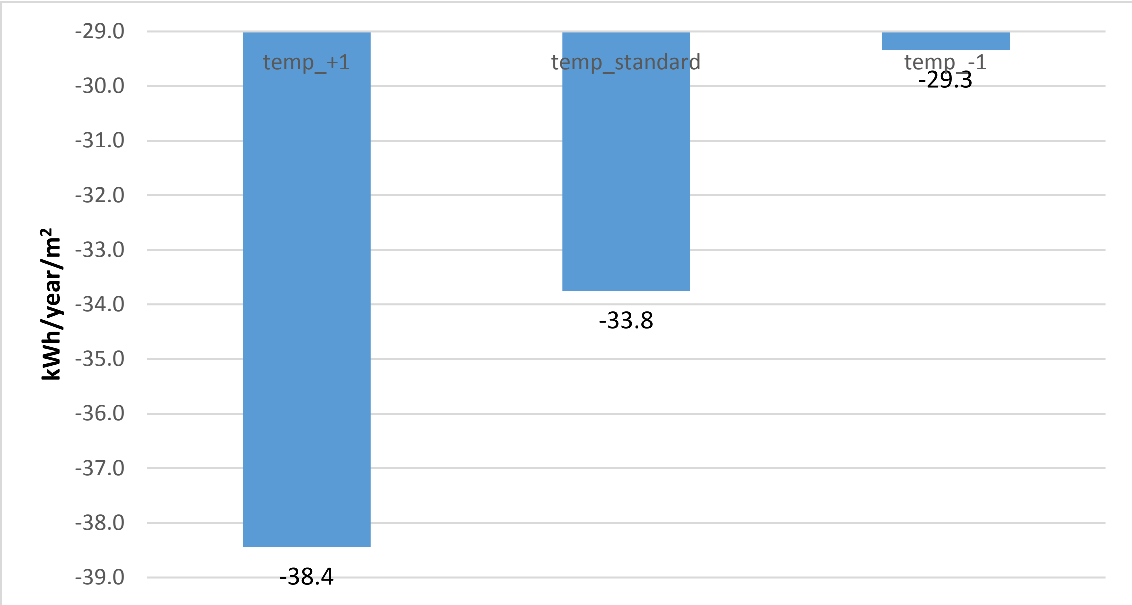


Figure 7.26 Cooling demand with one-degree temperature alteration

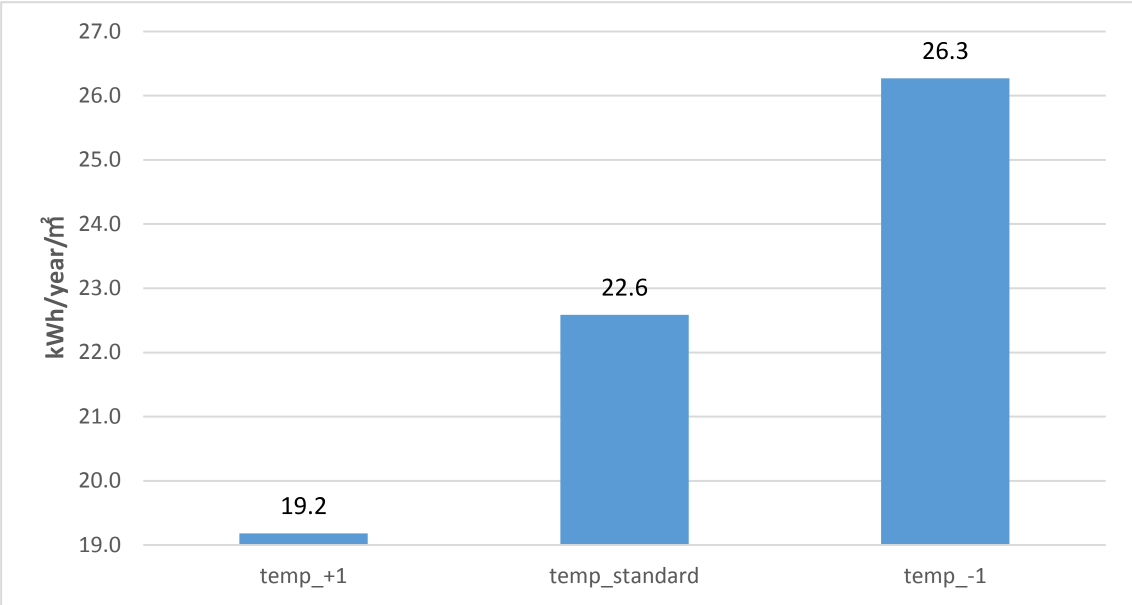


Figure 7.27 Heating demand with one-degree temperature alteration

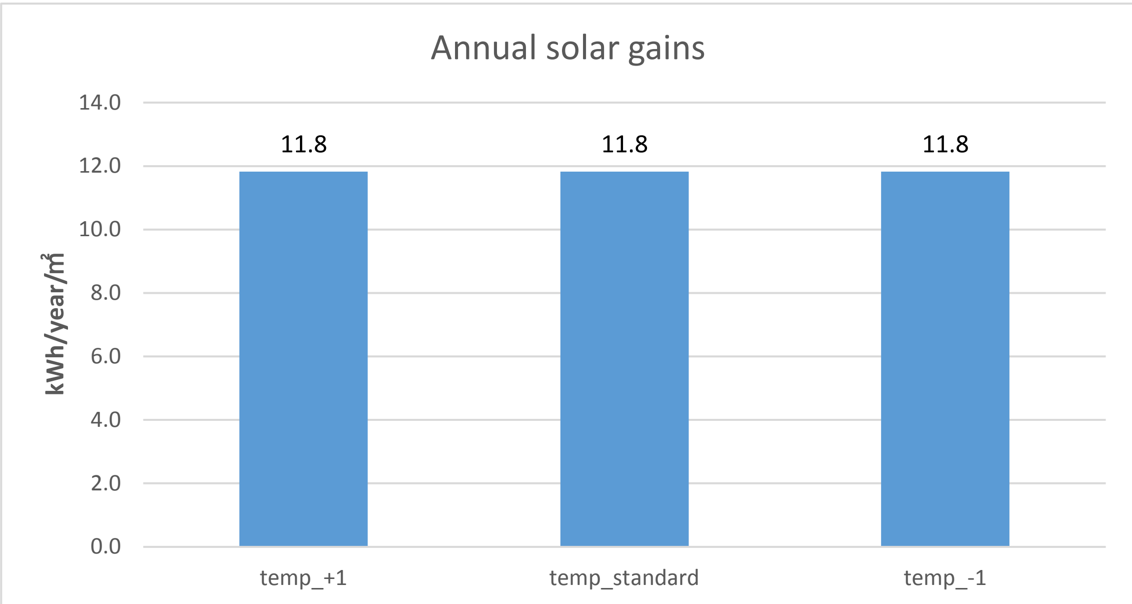


Figure 7.28 Annual solar gains with one-degree temperature alteration

Figure 7.26 to Figure 7.28 describe the impact of one-degree temperature change on energy demand and solar gains. As for the cooling demand, Figure 7.26 shows that this demand can increase by 13.6% with a one-degree increase compared to the standard temperature and reduce by 15.4% with one-degree decrease. Figure 7.27 shows that the heating demand can increase by 16.3% with the one-degree decrease when compared to the standard temperature, while it can reduce by 17.7% with the one-degree increase. When it comes to solar gains, it seems that there is no difference between the temperature alteration and solar gains, which is shown in Fig. 7.28. In a short, the results indicate that in terms of the overall effects, one-degree temperature reduction can contribute to around 2% to 3% (15.4% minus 13.6% or 17.7% minus 13.9%) energy-saving, and this range (2% -3%) is in agreement with the previous studies (Tarleton and Katz 1995).

7.3 Multinomial logistic regression of travel mode choices

Based on the data collected through the questionnaires, this section first describes and analyses the sample from the respondents on socioeconomic features, travel patterns, and self-evaluation on travelling. Following this, travel modes choice with these selected factors are regressed, analysed and compared from three cases so that the similarities and differences of their evaluations on mode choices can be explored. The holistic samples (the three study cases, N=427) are also analysed to eliminate the data shortage for the sake of accurate regressed results. By combining the above analysis, factors affecting travel modes choice can be concluded.

7.3.1 Sample description and analysis

Most scholars believe that compact urban development is the most important principle for low carbon development, which can lead to improving energy efficiency and shortening travel distances, and thus reducing transport energy consumption (Dhakal 2009; Mindali et al. 2004; Anderson et al. 2015). This section describes and analyses factors of three aspects from the surveyed samples: socioeconomic characteristics, travel patterns, and self-evaluation on travelling from the respondents. The sample size was decided to be by 5% to 10% of the overall population of the community for all the cases. It presents and analyses socioeconomic features, travel patterns, and self-evaluation from the respondents using the surveyed data.

(1) **Socioeconomic characteristics of the respondents**

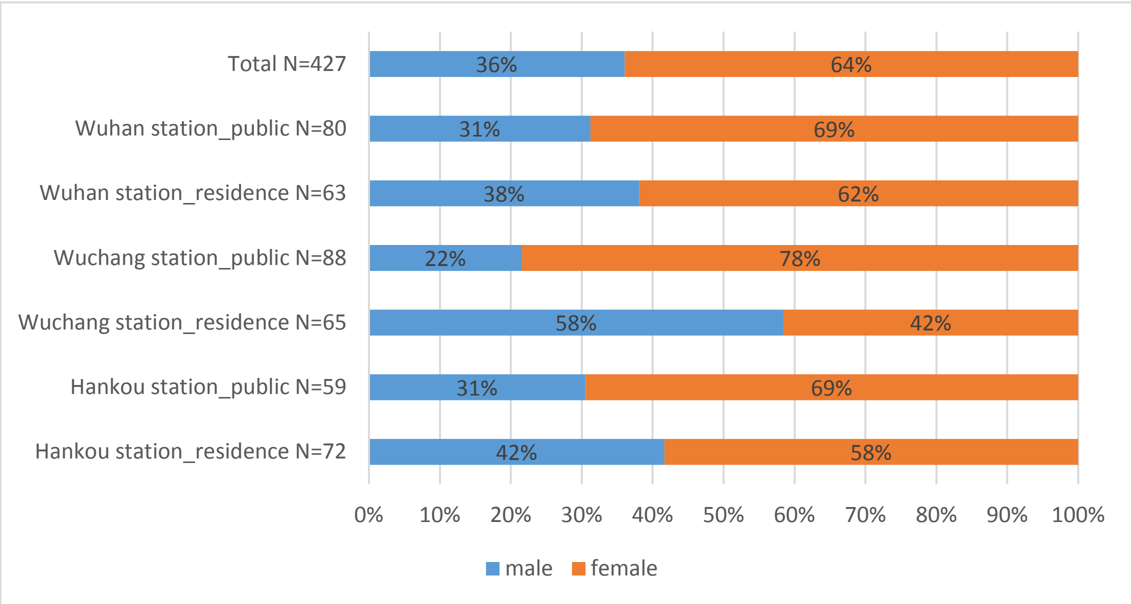


Figure 7.29 Gender distribution of the respondents in the three cases

According to Fig. 7.29, among these respondents from the three cases, firstly, in the case of Hankou station around, most people were female from both dwelling and public buildings, accounting for around 58 % and 69 % respectively. This trend was also observed in the case of Wuhan station (69 % female from public buildings vs 62% female from residential buildings). Lastly, around the Wuchang station around, most respondents were female from public buildings and male from dwellings (78% vs 58%). Overall, the respondents were female from both residential and public buildings.

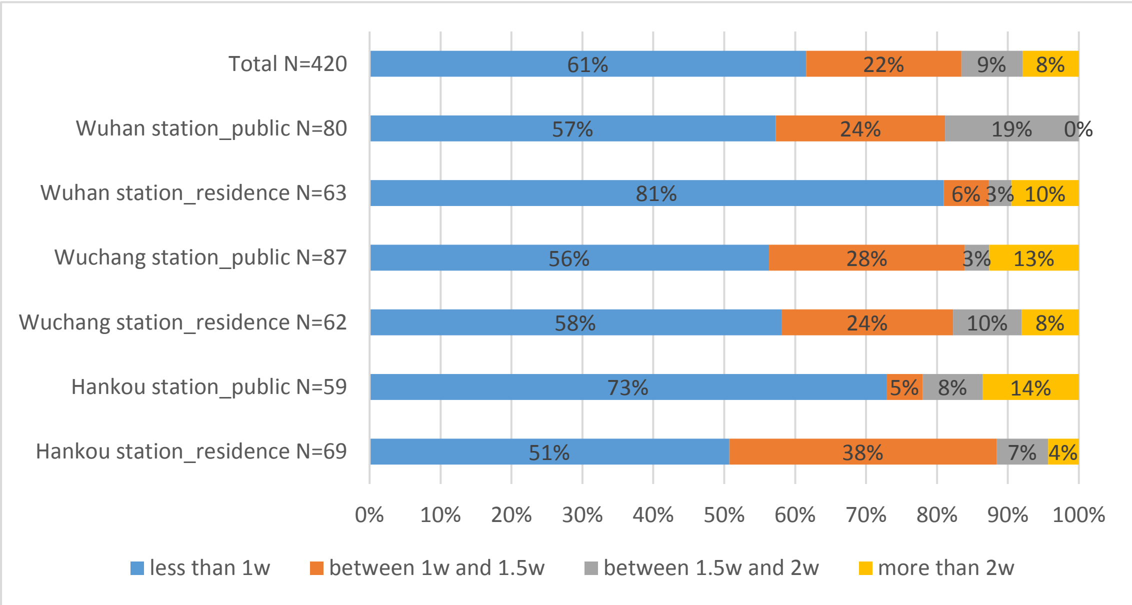


Figure 7.30 Distribution of family income of the respondents in the three cases

Figure 7.30 shows the monthly household income distribution from the respondents in the three cases. Most family monthly earnings were less than 10000 CNY (around 1100 GBP) from the respondents in the three cases, and this feature is quite noticeable from the respondents in public buildings around Hankou station and the residential buildings around Wuhan station. The average family monthly income level of the interviewees around Wuchang Station was the highest, while that of around Hankou Station was lowest.

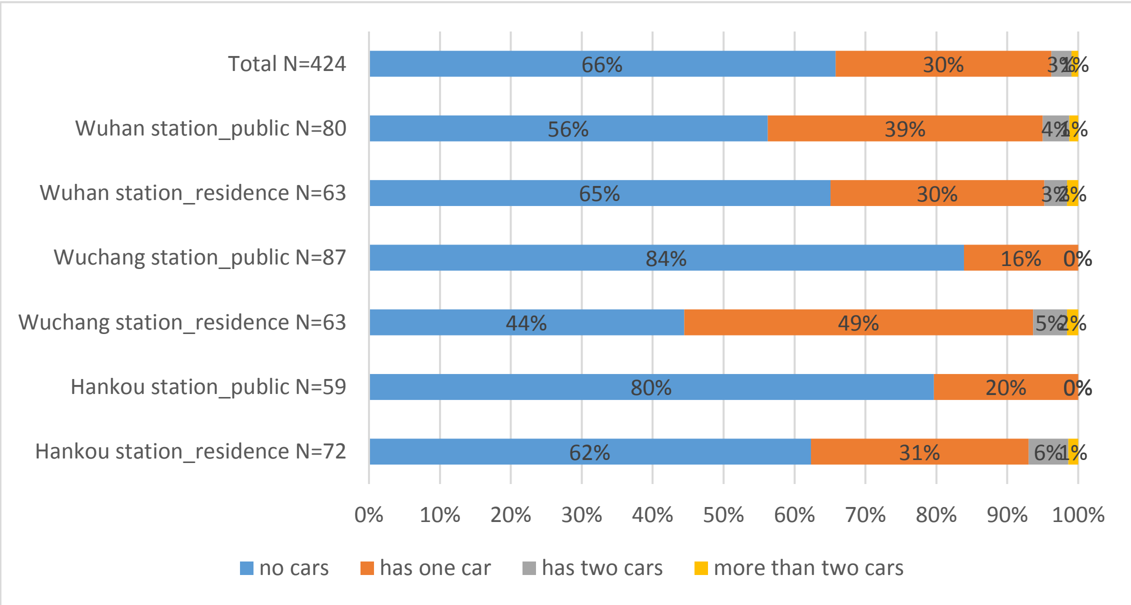


Figure 7.31 Distribution of car ownership of the respondents in the three cases

Regarding car ownership, Figure 7.31 shows that most of the families did not have a car, excluding the respondents from residential buildings around Wuchang stations. Meanwhile, very few families had two or more than two cars, and this phenomenon is evident from the people in the public buildings around Hankou and Wuchang stations. In general, 66% of the respondents did not have a car, followed by 30 % of individuals who had one car in their families. The remaining 4% of people had two or more cars.

(2) Travel patterns of the respondents

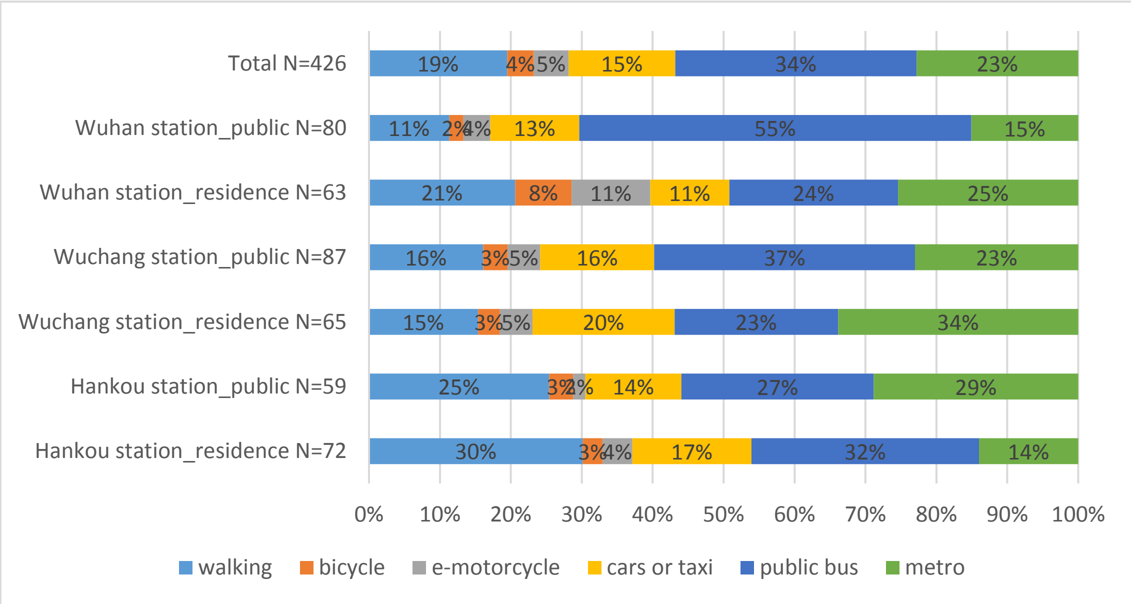


Figure 7.32 Distribution of modal splits of the respondents in the three cases

Figure 7.32 shows that the most three preferred transport modes are the underground, public buses, and walking in respondents from both public and residential buildings around the three case areas. Moreover, cars or taxis were also the prevalent transport modes among these interviewees, and this phenomenon was quite noticeable from the respondents in residential buildings around Wuchang station, as well as from those in the public buildings around Wuhan station.

In contrast, very few respondents took bicycle and e-motorcycle as their travel modes, with both less than 5%. Public buses were the most popular travel modes for respondents from all these three cases, accounting for 34%, followed by the underground (23%), and walking (19%). The remainder was by car or taxi (15%), e-motorcycle (5%), and bicycle (4%), respectively.

Regarding the travel time as shown in Figure 7.33, the majority of the respondents spent under 30 minutes for commuting, especially around the Hankou station. In contrast, very few respondents took more than one hour on their travelling, and around 35% of the people spent between 30mins and 60mins. Additionally, these results are also reflected from the average level, which is 49 % of respondents travelling for less than 30mins, and 35% between 30mins and 60mins. The rest travelled for more than 60mins.

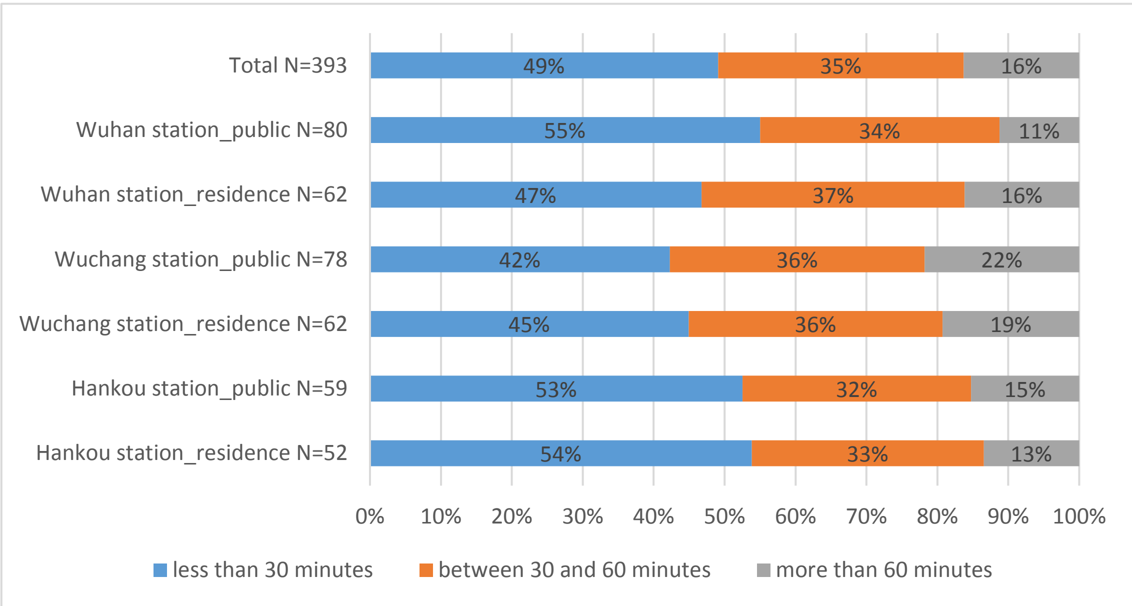


Figure 7.33 Travel time distribution on weekdays

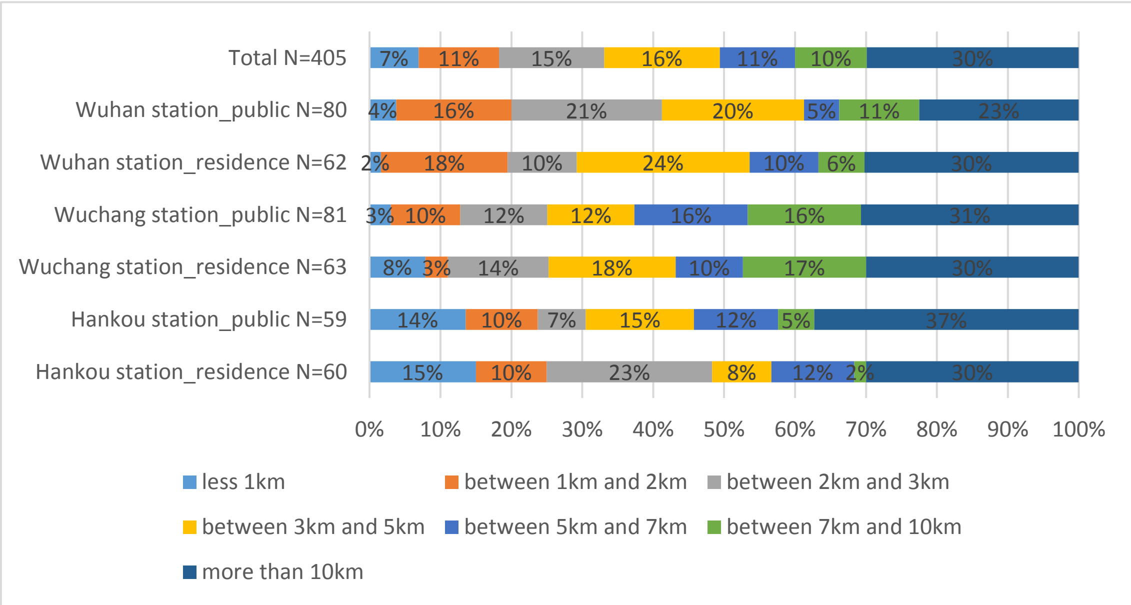


Figure 7.34 Travel distance distribution in the three cases

As for the travel distance shown in Fig. 7.34, it is quite noticeable that most of the respondents (around 30%) travelled more than 10 kilometres, followed by 16% between 3km and 5km, and 15% between 2km and 3km, respectively. In contrast, the lowest proportion, around 7% respondents, travelled within 1km. This figure indicates that most of the people lived far away from their working places, and this phenomenon was most apparent for the respondents around Hankou station.

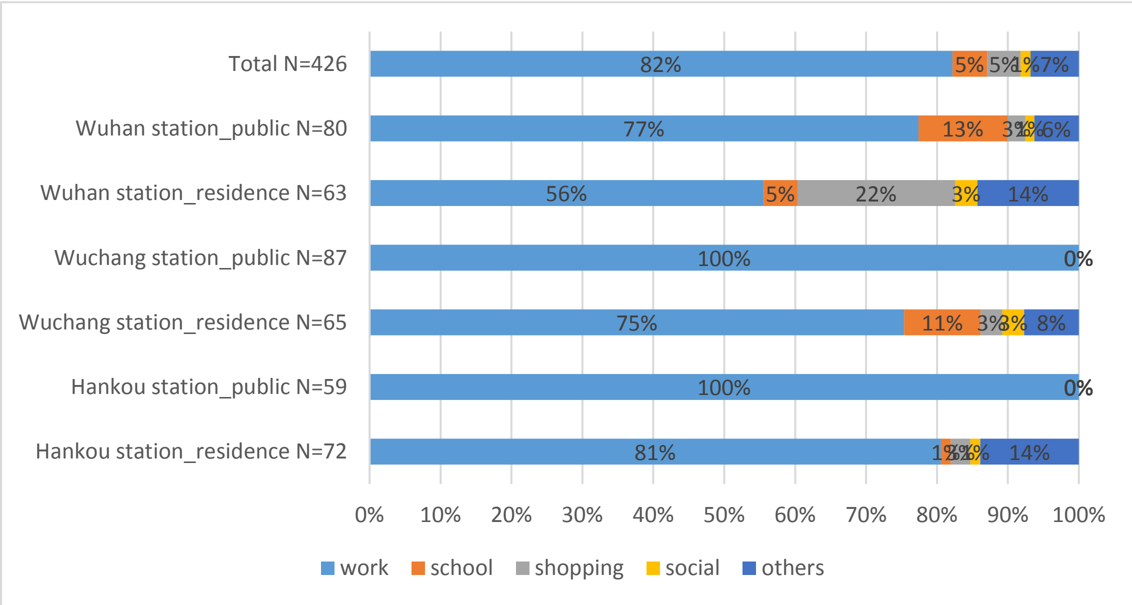


Figure 7.35 Travel purpose distribution in the three cases

Figure 7.35 presents and compares the travel purposes of the respondents around the three cases. The main purpose of respondents was travelling for work, representing around 80%. Conversely, only about 1% was for social purposes. Meanwhile, the purpose of going to school and shopping was equal, both standing at 5%. The remaining of around 7% was for other purposes. These data indicate that travelling for work is the respondents' primary purposes.

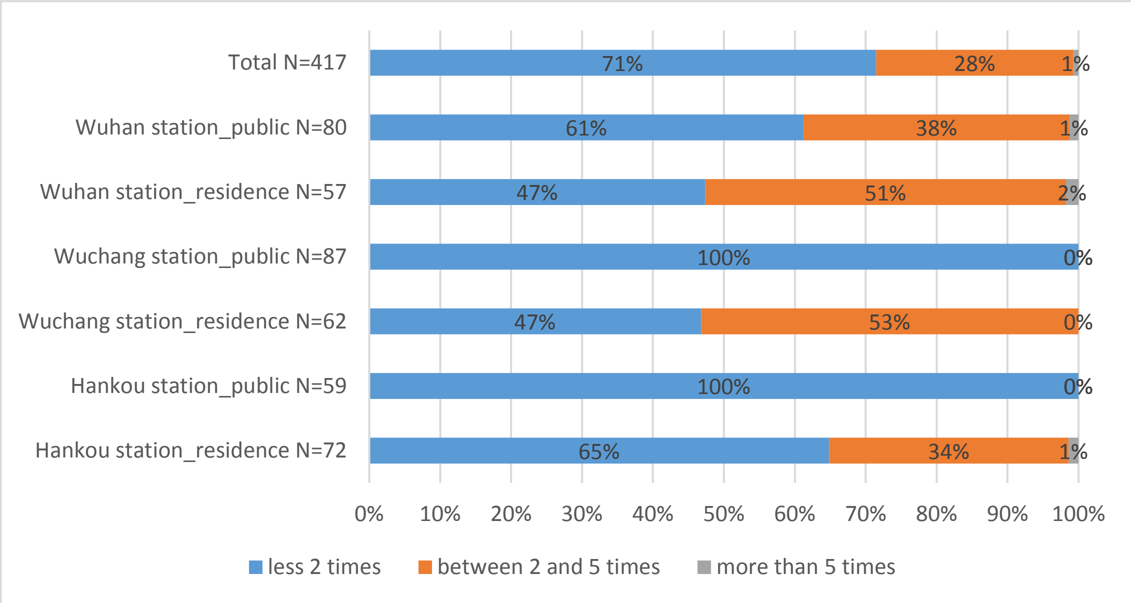


Figure 7.36 The distribution of daily trip frequency on weekdays in the three cases

Figure 7.36 above shows the daily travelling frequency on weekdays from the respondents around the three case areas. Most people (70%) travel to two times per day, and this is in accordance with their primary travel purpose. In contrast, very few respondents (around 1%) travelled more than five times per day.

(3) Travelling on self-evaluation

The following three graphs show and compare the respondents' evaluation of their travelling in the situations of congestion, comfort, and cost around the three stations.

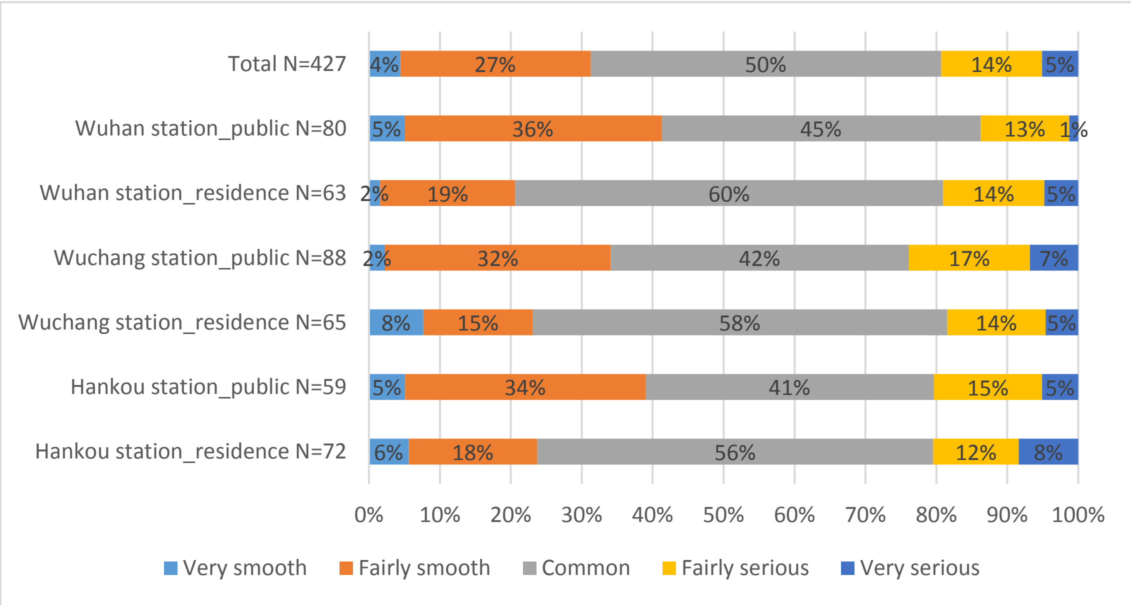


Figure 7.37 The distribution of travel congestion self-evaluation in the three cases

From Figure 7.37, it is evident that many respondents gave a "common level" of their judgments, accounting for around 50%, followed by a "fairly smooth" level (27%), and "fairly serious" level (14%). Meanwhile, the evaluation of "very smooth" and "very serious" occupied a much lower few proportions— less than 10%.

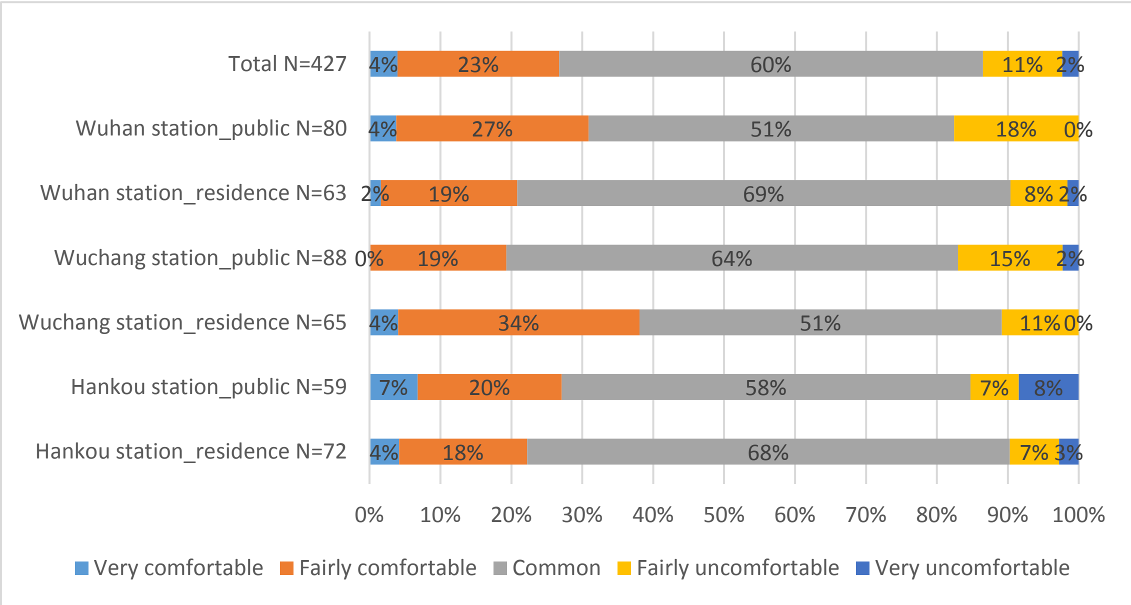


Figure 7.38 The distribution of comfort level self-evaluation in the three cases

Figure 7.38 shows and compares the distribution of comfort level self-evaluation from respondents around the three case areas. Generally, most of the respondents thought that the comfort level during their travelling was "common," representing around 60%, followed by "fairly comfortable" (23%), which was twice more than of "fairly uncomfortable" (11%). Finally, the remainder (around 6%) ranges between of "very comfortable" and "very uncomfortable."

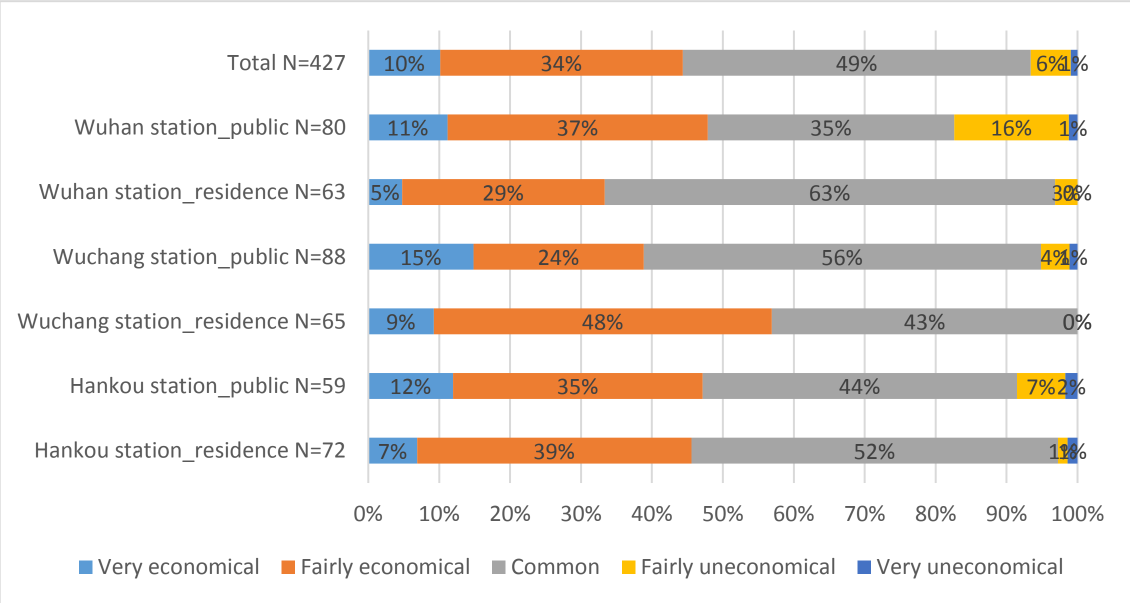


Figure 7.39 The distribution of economical level self-evaluation in the three cases

Figure 7.39 describes and compares the respondents' travelling cost assessments. Around half of the respondents believed that the travel cost was "common", followed by those who felt that it was "fairly economical" (34%). In contrast, only 1% of respondents thought it was "very uneconomical", and 10% thought it was "very economical." The remaining 6% thought it was "fairly uneconomical."

7.3.2 Multinomial logistic regression modelling

For multinomial logistic regression modelling of travel mode choice, the first step is to select and confirm the influencing factors. In this research, ten factors are selected, characterised by three categories: travel patterns, self-evaluation, and socioeconomic features (see Table 7.10). For the simplicity and clarity of the analysis, some variables are regrouped. For example, travel modes are regrouped into three categories based on their carbon dioxide emission characteristics, and trip purposes are classified into two groups: work and non-work purpose.

Following the modelling framework of discrete choice, Equations (7-1) and (7-2) express the probability of one travel mode being chosen as a function of a vector of explanatory variables X:

$$\ln(P_{transit}/P_{non-motorised}) = \beta_{a0} + \beta_{a1}x_1 + \beta_{a2}x_2 + \cdots + \beta_{a10}x_{10} \qquad (7-1)$$

$$\ln\left(P_{driving}/P_{non-motorised}\right) = \beta_{b0} + \beta_{b1}x_1 + \beta_{b2}x_2 + \cdots + \beta_{b10}x_{10} \qquad (7-2)$$

where= P is the probability of mode choice; X is independent variables, consisting of the socioeconomic characteristics of the travellers, the characteristics of travel patterns and the self-evaluation on travelling; β is the coefficients; β_{a0} and β_{b0} are constants.

In the modelling process, all the ten potential independent variables were considered. Then, based on the statistical test results, less-significant independent variables were removed. The best models of the travelling mode choices were established with all significant variables.

Table 7.10 Description of variables

Categories		Factors	Description
Type of Variables	Factor grouping		
Dependent		Trip modes	1 ="non-motorised "; 2 ="transit";3 ="driving"
Independent	Travel patterns of the respondents	Travel time (x1)	1="less than 30 minutes";
			2="between 30 and 60 minutes";
			3="between 60 and 90 minutes";
			4="between 90 and 120 minutes";
			5="more than 120 minutes";
		Travel distance(x2)	1="less than 1 km";
			2="between 1 and 2 km";
			3="between 2 and 3 km";
			4="between 3 and 5 km";
			5="between 5 and 7 km";
			6="between7 and 10 km";
			7="more than 10 km."
		Travel purpose(x3)	1 = "work"; 2 = "non-work";
		Daily travel frequency (x4)	1= "no more than 2 times ";2="between 2 and 5 times ";3="more than 5 times"
	Self-evaluation on travel from the respondents	Congestion situation in the process of travelling(x5)	1 ="very smooth"; 2=" fairly smooth";3="common";4=" fairly serious";5="very serious"
		Comfort level in the process of travelling(x6)	1 ="very comfortable";
			2 =" fairly comfortable"; 3 ="common";
			4 =" fairly uncomfortable";
			5 ="very uncomfortable"
		Economical level in the process of travelling(x7)	1="very economical";2=" fairly economical"; 3="common"; 4=" fairly uneconomical";
			5="very uneconomical."
	Socioeconomic characteristics of the respondents	Gender(x8)	0 ="male", 1 ="female"
		Car ownership in family (x9)	0="no cars"; 1="has one car";
			2="has two cars"; 3="no less than 3 cars"
		Household monthly income(x10)	1="no more than 10000 CNY ";
			2="between 10000 and 15000";
			3=" between 15000 and 20000."
			4="more than 20000."

Note: £1 equals to around 9.0 CNY

7.3.3 Results of the logistic regression modelling

For this section, the results of logistic regression modelling from three cases are presented in the following parts. For each case, the results of the Case Processing Summary, Model Fitting Information, Likelihood Ratio Tests, and finally, the Parameter Estimates, are displayed. The travel mode choice from holistic samples is also presented and analysed.

Case1: around Hankou railway station

Table 7.11 presents the basic information of the Case 1 (Around Hankou Station). There were around 131 samples from Case 1, with about 55% female respondents being female. For the transport modes distribution, most people use transit as their travelling modes, followed by non-motorised transport and driving. Regarding the trip purposes, around 90% of respondents travelled for work, and the remainder was for other the non-working purposes.

Table 7.11 Case processing summary

Case Processing Summary			
		N	Marginal Percentage
Trip modes	non-motorised	45	34.4%
	transit	67	51.1%
	driving	19	14.5%
Gender	male	59	45.0%
	female	72	55.0%
Trip purpose	work	117	89.3%
	non-work	14	10.7%
Valid		131	100.0%
Missing		0	
Total		131	
Subpopulation		123[a]	

a. The dependent variable has only one value observed in 121 (98.4%) subpopulations.

Table 7.12 shows the model fitting information (Final) against one in which all the parameter coefficients are zero (Null hypothesis). From Table 7.12, it reads that the final model is better than the model with the intercept only because the value of -2 Log Likelihood is smaller. Secondly, since the significance level (P value) of the test is less than 0.05, the Null hypothesis can be rejected.

Table 7.12 Model fitting information

Model Fitting Information				
Model	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	**Sig.**
Intercept Only	256.612			
Final	166.102	90.510	20	**.000**

Table 7.13 describes the Likelihood Ratio Tests, and the independent variables with the boldface show the statistical significance that exists in the model. For example, variables such as family monthly income, travel distance, genders of the respondents, their purposes, etc. have statistical significance in the modelling.

Table 7.13 Likelihood ratio tests

Likelihood Ratio Tests				
Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	166.102[a]	.000	0	.
Income	182.639	16.537	2	**.000**
Number	167.560	1.459	2	.482
Frequency	168.947	2.845	2	.241
Time	170.992	4.890	2	.087
Distance	181.023	14.921	2	**.001**
Congestion	172.867	6.765	2	**.034**
Comfort	172.193	6.092	2	**.048**
Economical	168.692	2.590	2	.274
Gender	180.192	14.091	2	**.001**
Purpose	173.342	7.241	2	**.027**
The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The				

null hypothesis is that all parameters of that effect are 0.
a. This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

In **Table 7.14**, the non-motorised mode is set as the reference category in the model. The parameters in the table with boldface have a significant level in the modelling.

Table 7.14 Parameter estimates

Parameter Estimates									
Trip modes[a]		B	Std. Error	Wald	df	Sig.	**Exp(B)**	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
Transit	**Intercept**	-4.260	1.711	6.198	1	**.013**			
	Income	.188	.309	.371	1	.543	1.207	.659	2.212
	Number	-.409	.520	.618	1	.432	.665	.240	1.841
	Frequency	.806	.578	1.946	1	.163	2.239	.721	6.947
	Time	.591	.317	3.480	1	.062	1.806	.970	3.361
	Distance	.343	.125	7.534	1	**.006**	**2.027**	1.103	1.801
	Congestion	-.019	.317	.004	1	.953	.981	.527	1.828
	Comfort	.161	.340	.224	1	.636	1.174	.604	2.285
	Economical	-.073	.332	.048	1	.827	.930	.486	1.781
	[Gender=0]	1.017	.480	4.485	1	**.034**	**2.765**	1.079	7.086
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	.777	.858	.820	1	.365	2.175	.404	11.698
	[Purpose=2]	0[b]	.	.	0	.	.	.	.
Driving	**Intercept**	-9.580	3.482	7.568	1	**.006**			
	Income	1.702	.529	10.362	1	**.001**	**5.484**	1.946	15.456
	Number	.284	.733	.151	1	.698	1.329	.316	5.589
	Frequency	-.328	1.135	.084	1	.773	.720	.078	6.665
	Time	.133	.465	.082	1	.774	1.143	.460	2.841
	Distance	.706	.226	9.748	1	**.002**	**1.409**	1.301	3.158
	Congestion	-1.214	.566	4.595	1	**.032**	**3.367**	1.110	10.217
	Comfort	-1.171	.621	3.550	1	.060	.310	.092	1.048
	Economical	.778	.570	1.863	1	.172	2.177	.712	6.655
	[Gender=0]	3.417	1.149	8.852	1	**.003**	**3.482**	3.209	289.522
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	**-2.612**	**1.276**	**4.188**	**1**	**.041**	**.073**	.006	.895
	[Purpose=2]	0[b]	.	.	0	.	.	.	.

a. The reference category is: non-motorised .
b. This parameter is set to zero because it is redundant.

Analysis of travel mode choice in Case 1

The Parameter Estimates include two parts for each trip purpose. Part 1 shows the effects of the independent variables on the odds ratio (**EXP(B))** of choosing transit over the reference mode, which is NMM. Part 2 shows the odds ratio of choosing driving over NMM.

The significant coefficient (B value) for the variable of **trip distance** is positive and statistically significant in both two models (part 1 and part 2). The positive sign indicates that for longer trip distances the travellers around Hankou station are less likely to choose non-motorised modes. Rather, they tend to use transit and automobile. This result confirms the expected importance of the public transport system performance to travellers' decision on travel mode choice. The odds ratios Exp (B) in **Table 7.14** show that the models allow quantitative assessment of travellers' mode preferences. For example, the odds ratio of taking transit over non-motorised has a value of 2.027, meaning that the likelihood of choosing transit is 2.027 times higher than choosing to NMM for every kilometre increase in trip distance, or else being equal. Similarly, the probability of choosing the driving mode is 1.409 times higher than choosing walking or cycling when the trip distance becomes one kilometre longer.

Furthermore, from these two odds ratios, one can infer the travellers' preference of transit outweighing driving when travel distance increases. This is because both odds ratios use NMM as the reference category, and the ratio of the two odds ratio, 2.027/1.409 = 1.44, gives the odds of choosing transit over driving. When the trip distance increases by one kilometre, the likelihood of a traveller choosing transit is 1.44 times greater than choosing driving. This result is not surprising, given the public transport available around the Hankou station.

Results of the regression analysis also verify the expected effects of income on driving mode choice. As income increases, people are more likely to choose the drive mode, and this phenomenon is obvious as the magnitudes of income effects on mode choice are statistically significant with the odds ratio of 5.484. Other variables such as congestion, gender, and purpose also influence driving decisions.

The final model in Case 1:

$$\mathrm{Y} = \ln(P_{transit}/P_{non-motorized}) = -4.260 + 0.343\ distance + 1.017 gender_{=0}$$

$$\mathrm{Y} = \ln\left(P_{driving}/P_{non-motorized}\right)$$
$$= -9.580 + 1.702\ income + 0.706\ distance + 3.417 gender_{=0} - 1.214\text{congestion} - 2.612 purpose_{=1}$$

Case2: around Wuchang railway station

Table 7.15 presents the basic information of Case 2. There were around 152 samples, with about 63% being female respondents. For the transport modes distribution, 58.6% of people use transit as their travel mode, followed by non-motorised (23.7%) and driving (17.8%). Regarding the trip purposes, 89.5% of respondents travelled for work, and the remaining 10.5% travelled for non-work purposes.

Table 7.15 Case processing summary

Case Processing Summary			
		N	Marginal Percentage
Trip modes	non-motorised	36	23.7%
	transit	89	58.6%
	driving	27	17.8%
Gender	male	57	37.5%
	female	95	62.5%
Trip purpose	work	136	89.5%
	non-work	16	10.5%
Valid		152	100.0%
Missing		0	
Total		152	
Subpopulation		142[a]	
a. The dependent variable has only one value observed in 140 (98.6%) subpopulations.			

Table 7.16 Model fitting information

Model Fitting Information				
Model	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	289.521			
Final	172.928	116.593	20	**.000**

Table 7.17 likelihood ratio tests

Likelihood Ratio Tests				
Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	172.928[a]	.000	0	.
Income	175.342	2.414	2	.299
Number	183.154	10.226	2	**.006**
Frequency	174.431	1.503	2	.472
Time	182.644	9.716	2	**.008**
Distance	201.663	28.735	2	**.000**
Congestion	176.576	3.648	2	.161
Comfort	185.289	12.361	2	**.002**
Economical	180.662	7.734	2	**.021**
Gender	176.684	3.756	2	.153
Purpose	178.045	5.117	2	.077

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a. This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

Table 7.16 and Table 7.17 describes the Likelihood Ratio Tests and Parameter Estimates, respectively. These two tables show that parameters within bold are statistically significant and these variables would exist in the final model. For example, variables such as the number of cars owned, trip time, distance, etc. have statistical significance in the model.

Table 7.18 is the result of parameter estimates. The coefficient for the variable of trip distance is positive and statistically significant in both two models (transit vs. non-motorised and driving vs. non-motorised). The odds ratios Exp (B) in Table 7.18 allow quantitative assessment of the modal preferences. For example, the odds ratio of taking transit over non-motorised modes has a value of 2.549, meaning that the likelihood of choosing transit is 2.549 times higher than choosing to walk or cycling for every kilometre increase in trip distance. Similarly, the likelihood of choosing the driving mode is 2.535 times greater than choosing walking or cycling when the trip distance becomes one kilometre longer. Furthermore, from these two odds ratios, one can infer the travellers' preference of transit is almost the same as driving because both odds ratios use NMM as the reference category, the ratio of the two odds ratios, 2.549/2.535 =1.001, gives the odds of choosing transit marginally over driving when the trip distances increase one kilometre. Other variables, such as car ownership and travel cost, also have significant effects on the driving choice.

Table 7.18 Parameter estimates

Parameter Estimates									
Trip modes[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
Transit	Intercept	-8.330	2.733	9.288	1	.002			
	Income	-.481	.345	1.950	1	.163	.618	.314	1.215
	Number	.963	.685	1.973	1	.160	2.619	.683	10.033
	Frequency	-.594	.716	.688	1	.407	.552	.136	2.246
	Time	1.343	.710	3.573	1	.059	3.830	.952	15.410

	Distance	.936	.225	17.287	1	**.000**	**2.549**	1.640	3.962
	Congestion	-.126	.435	.084	1	.772	.881	.376	2.068
	Comfort	1.266	.540	5.494	1	**.019**	**3.547**	1.230	10.223
	Economical	.619	.435	2.026	1	.155	1.858	.792	4.358
	[Gender=0]	-.370	.642	.333	1	.564	.690	.196	2.429
	[Gender=1]	0^b	.	.	0	.	.	.	.
	[Purpose=1]	.435	.858	.257	1	.612	1.545	.287	8.305
	[Purpose=2]	0^b	.	.	0	.	.	.	.
	Intercept	-10.456	3.244	10.387	1	**.001**			
	Income	-.571	.419	1.852	1	.174	.565	.248	1.286
	Number	2.134	.759	7.904	1	**.005**	**8.450**	1.908	37.417
	Frequency	-1.011	.835	1.467	1	.226	.364	.071	1.868
	Time	.367	.785	.218	1	.640	1.443	.310	6.724
	Distance	.930	.249	13.989	1	**.000**	**2.535**	1.557	4.f
Driving	Congestion	.522	.490	1.135	1	.287	1.685	.645	4.402
	Comfort	-.153	.657	.054	1	.816	.858	.237	3.108
	Economical	-1.529	.593	6.654	1	**.010**	**4.615**	1.444	14.749
	[Gender=0]	.680	.738	.849	1	.357	1.974	.465	8.386
	[Gender=1]	0^b	.	.	0	.	.	.	.
	[Purpose=1]	2.532	1.340	3.573	1	.059	12.585	.911	173.881
	[Purpose=2]	0^b	.	.	0	.	.	.	.

a. The reference category is: non-motorised.

b. This parameter is set to zero because it is redundant.

Final model in the Case 2

$$Y = \ln(P_{transit}/P_{non-motorized}) = -8.330 + 0.936\, distance + 1.266\, comfort$$

$$\mathrm{Y} = \ln\left(P_{driving}/P_{non-motorized}\right)$$
$$= -10.456 + 2.134\, number + 0.930\, distance - 1.529 economical$$

Case3: around Wuhan railway station

As with the previous cases, Table 7.19 presents the basic information of the Case 3. There were around 143 samples, with around 66% being female respondents. For the transport modes distribution, 60.8% of people use transit as their travel modes, followed by non-motorised (27.3%) and driving (11.9%). Regarding the trip purposes, 67.8% of respondents travelled for work, and the remainder travelled for non-work purposes.

Table 7.19 Case processing summary

Case Processing Summary			
		N	Marginal Percentage
Trip modes	non-motorised	39	27.3%
	transit	87	60.8%
	driving	17	11.9%
Gender	male	49	34.3%
	female	94	65.7%
Trip purpose	work	97	67.8%
	non-work	46	32.2%
Valid		143	100.0%
Missing		0	
Total		143	
Subpopulation		141[a]	

a. The dependent variable has only one value observed in 141 (100.0%) subpopulations.

Table 7.20 shows the modelling fitting information. From this table, one can see that the overall significance level for the final model is zero (P value <.05), and this means that the final model has statistical significance. Therefore, the next step is to explore which variables show statistical significance and in the final model.

Table 7.20 Model fitting information

Model Fitting Information				
Model	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	260.218			
Final	186.587	73.631	20	**.000**

Table 7.21 describes the Likelihood Ratio Tests. From this table, it can be seen that the variables such as family monthly- income, travel time, the degree of comfort level, and travel cost has a statistical significance that would exist in the model.

Table 7.21 Likelihood ratio tests

Likelihood Ratio Tests				
Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	186.587[a]	.000	0	.
Income	203.379	16.792	2	**.000**
Number	191.508	4.921	2	.085
Frequency	187.724	1.137	2	.566
Time	193.302	6.715	2	**.035**
Distance	192.329	5.742	2	.057
Congestion	192.193	5.606	2	.061
Comfort	192.620	6.033	2	**.049**
Economical	192.901	6.314	2	**.043**
Gender	186.905	.318	2	.853
Purpose	190.324	3.737	2	.154

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a. This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

Table 7.22 is the result of parameter estimates. The coefficient for the variable of trip distance in transit modes is positive and statistically significant. The odds ratio Exp(B) in Table 7.22 has a value of 1.433, meaning that the likelihood of choosing transit is 1.433 times higher than choosing non-motorised modes for every kilometre increase in trip distance. In addition, in the driving model, variables such as family monthly income, and three evaluation indices also have significant effects on the choice of driving over NMM. However, the variable of travelled distance shows no significance in the driving model of the Case 3.

Table 7.22 Parameter estimates

Parameter Estimates									
Trip modes[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
Transit	Intercept	-1.167	1.436	.660	1	.416			
	Income	.508	.352	2.092	1	.148	1.663	.835	3.312
	Number	-.291	.408	.509	1	.475	.748	.336	1.662
	Frequency	-.450	.425	1.122	1	.289	.638	.277	1.466
	Time	.875	.459	3.640	1	.056	2.398	.976	5.891
	Distance	.360	.173	4.316	1	**.038**	**1.433**	1.021	2.013
	Congestion	.072	.300	.058	1	.809	1.075	.597	1.937
	Comfort	-.174	.397	.192	1	.661	.840	.386	1.831
	Economical	-.096	.330	.085	1	.770	.908	.476	1.733
	[Gender=0]	-.222	.500	.198	1	.656	.801	.301	2.131
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	-.066	.498	.018	1	.894	.936	.353	2.484
	[Purpose=2]	0[b]	.	.	0	.	.	.	.
Driving	Intercept	-7.433	2.728	7.425	1	.006			
	Income	1.626	.464	12.299	1	**.000**	**5.083**	2.049	12.611
	Number	.720	.515	1.956	1	.162	2.054	.749	5.630
	Frequency	-.345	.756	.208	1	.648	.708	.161	3.118
	Time	-.020	.711	.001	1	.977	.980	.243	3.947
	Distance	.580	.310	3.488	1	.062	1.786	.972	3.281
	Congestion	-1.217	.557	4.767	1	**.029**	3.376	1.133	10.062
	Comfort	1.570	.715	4.822	1	**.028**	.208	.051	.845
	Economical	-1.140	.575	3.928	1	**.047**	3.127	1.013	9.656
	[Gender=0]	-.466	.927	.252	1	.615	.628	.102	3.861
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	-1.531	.887	2.977	1	.084	.216	.038	1.231
	[Purpose=2]	0[b]	.	.	0	.	.	.	.

a. The reference category is: non-motorised.

b. This parameter is set to zero because it is redundant.

The final model in Case 3

$$Y = \ln(P_{transit}/P_{non-motorized}) = 0.360\ distance$$

$$Y = \ln\left(P_{driving}/P_{non-motorized}\right)$$
$$= 1.626\ \text{income}\ - 1.217\ congestion + 1.570\ comfort$$
$$- 1.140\ economical - 7.433$$

Three cases combined analysis

To eliminate the lack of the samples data, this part uses the data from three selected areas as a whole in order to analyse mode choices between the selected factors. Table 7.23 is the Case Processing Summary of 426 samples. It clearly shows that most of the respondents are female, accounting for 61.3% of the total number of respondents. As for the trip purpose, 82.3% of people are travelling for work. Finally, for the travel modes, 56.8% people use transit, followed by 28.2% using non-motorised modes and 15% with driving modes.

Table 7.23 Case processing summary

Case Processing Summary			
		N	Marginal Percentage
Trip modes	non-motorised	120	28.20%
	transit	242	56.80%
	driving	64	15.00%
Trip purpose	work	350	82.20%
	non-work	76	17.80%
Gender	male	165	38.70%
	female	261	61.30%
Valid		426	100.00%
Missing		0	
Total		426	
Subpopulation		384[a]	

a. The dependent variable has only one value observed in 375 (97.7%) subpopulations.

Table 7.24 shows the modelling fitting information. From this table, one can see that the overall significance level for the model is zero (P value <=.05), and this means that the model has statistical significance.

Table 7.24 Model fitting information

Model Fitting Information				
Model	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	805.492			
Final	583.641	221.851	20	**.000**

Table 7.25 and Table 7.26 describes the Likelihood Ratio Tests, and Parameter Estimates, respectively. For these two tables, the parameters in bold are the effective factors that would exist in the final model. For example, factors such as family monthly income, travel time, the degree of comfort level, and travel cost have statistical significance in the model.

Table 7.25 Likelihood ratio tests

Likelihood Ratio Tests				
Effect	Model Fitting Criteria	Likelihood Ratio Tests		
	-2 Log Likelihood of Reduced Model	Chi-Square	df	Sig.
Intercept	583.641[a]	.000	0	.
Income	595.142	11.501	2	**.003**
Number	595.089	11.449	2	**.003**
Frequency	585.147	1.506	2	.471
Time	603.119	19.478	2	**.000**
Distance	632.451	48.810	2	**.000**
Congestion	599.654	16.013	2	**.000**
Comfort	600.350	16.709	2	**.000**
Economical	591.706	8.066	2	**.018**
Gender	590.725	7.085	2	**.029**
Purpose	583.963	.322	2	.851

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.
a. This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

Table 7.26 Parameter estimates

Parameter Estimates									
Trip modes[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
transit	**Intercept**	-2.791	.875	10.165	1	**.001**			
	Income	.076	.162	.219	1	.640	1.079	.786	1.481
	Number	-.225	.263	.732	1	.392	.798	.476	1.338
	Frequency	.028	.281	.010	1	.920	1.029	.593	1.783
	Time	.657	.229	8.234	1	**.004**	**1.928**	1.231	3.020
	Distance	.511	.084	36.851	1	**.000**	**1.855**	1.414	1.966
	Congestion	-.027	.183	.022	1	.883	.974	.680	1.393
	Comfort	.209	.219	.910	1	.340	1.233	.802	1.894
	Economical	-.040	.187	.047	1	.829	.961	.666	1.385
	[Gender=0]	.104	.280	.138	1	.710	1.110	.641	1.920
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	-.020	.347	.003	1	.955	.980	.497	1.934
	[Purpose=2]	0[b]	.	.	0	.	.	.	.
driving	**Intercept**	-5.695	1.294	19.377	1	**.000**			
	Income	.594	.199	8.910	1	**.003**	**1.812**	1.226	2.677
	Number	.637	.302	4.456	1	**.035**	**1.891**	1.047	3.416
	Frequency	-.408	.413	.975	1	.323	.665	.296	1.495
	Time	-.126	.312	.164	1	.685	.881	.479	1.623
	Distance	.618	.119	26.781	1	**.000**	**1.667**	1.468	2.344
	Congestion	-.843	.260	10.501	1	**.001**	**0.324**	1.395	3.869
	Comfort	.888	.311	8.141	1	**.004**	**.411**	.223	.757
	Economical	-.623	.274	5.171	1	**.023**	**1.864**	1.090	3.188
	[Gender=0]	.944	.389	5.872	1	**.015**	**2.570**	1.198	5.514
	[Gender=1]	0[b]	.	.	0	.	.	.	.
	[Purpose=1]	-.257	.487	.279	1	.597	.773	.298	2.007
	[Purpose=2]	0[b]	.	.	0	.	.	.	.

a. The reference category is: non-motorised.
b. This parameter is set to zero because it is redundant.

The modelling outcome shows the effects of the independent variables on the odds ratio EXP (B) of choosing transit model vs. the reference model (non-motorised modes), as well as the odds ratio of choosing driving vs. the non-motorised modes (NMM)

Firstly, the variable of trip distance is positive and statistically significant in both models (transit and driving). The positive sign shows that, for longer trips, travellers around the three stations are less likely to use non-motorised modes. Rather, they tend to take transit and driving modes. The odds ratios Exp (B) shown in Table 7.26 allow quantitative assessment of the modal preferences. For example, the odds ratio of taking transit over NMM has a value of 1.855, meaning that the likelihood of the option in transit is 1.855 times higher than NMM for every one-kilometre increase in trip distance. Similarly, the probability of choosing driving mode is 1.667 times greater than NMM when the trip distance becomes one kilometre longer. Furthermore, from these two odds ratios, one can infer the preference is for transit over driving. Because both odds ratios use NMM as the reference mode, the ratio of the two odds ratios, 1.855/1.667 = 1.113, gives the odds of choosing transit over driving. This means that when the trip distance increases by one kilometre, the likelihood of choosing transit modes is 1.113 times greater than driving modes. This result is not surprising around three stations due to huge population mobility and a significant number of public transport networks and nodes provided. Results of the regression analysis also verify the expected effects of travel time on the choice of transit modes but do not show statistical significance on the choice of driving modes. As travel time increases, people are more likely to choose the transit modes than NMM. The magnitudes of travel time on the choice of transit modes are statistically significant with the odds ratio of 1.928.

Secondly, in the driving model, variables such as family income, car ownership, indicators of self-evaluation, and the number of males is also statistically significant. The effects of income on driving mode choice are small yet statistically significant (with an estimated odds ratio of 1.812). The number of cars-owned has noticeable effects on driving decisions, with an odds ratio of 1.891 of driving over NMM when there is another motor vehicle added to the household. In conclusion, **travel time and distance are the primary factors to transit modes, while family monthly income, car ownership, and their travel self-assessment on congestion and comfort are the main driving forces of driving modes.**

Nevertheless, travel time and travel frequency seem to have no significant effects on driving mode choice. Interestingly, variables representing travellers' self-evaluation indicators almost display a negative relationship with driving modes. However, decisions between transit and NMM, their coefficients show no statistical significance. This result suggests that, despite the rapid growth in family income and motorisation rate, travellers prefer transit modes because of long-time and long- distance travelling.

The final model in three cases

$$Y = \ln(P_{transit}/P_{non-motorized}) = -2.791 + 0.657\ time + 0.511\ distance$$

$$\begin{aligned} \mathrm{Y} = \ \ln\left(P_{driving}/P_{non-motorized}\right) \\ &= -5.695 + 0.594\ income + 0.637\ number + 0.618\ \mathrm{distance} \\ &- 0.843\ \mathrm{congestion} + 0.888\ \mathrm{comfort} - 0.623\ \mathrm{economical} \\ &+ 0.944 gender_{=0} \end{aligned}$$

7.3.4 Comparison of these three cases

This section compares and analyses three selected cases. The statistically significant variables in the regression model from each case are sorted, and then compared and analysed. Travelled distance is one of the most important factors in the model from three cases, both in transit model and driving model. In these three cases, most travellers prefer transit to driving modes. Conversely, the factor of family income level shows the most significant magnitude in the driving model around Wuhan station, with an odds ratio 5.083.

According to the on-site survey, although there are more underground stations and public bus routes available around Wuchang and Hankou stations compared to Wuhan station (especially in the city centre), there are many other options of modal splits such as driving and taxis. Around Wuhan station, there are very few travel modes available save for the underground stations and limited public buses due to the underconstruction of these areas and the poor infrastructure services. Therefore, commuting is inconvenient for people around Wuhan station compared to the other two cases, especially for the driving mode. This indicates that the availability of major public transport can have a powerful influence on the modal splits. According to these three cases, commuters' decisions on transit modes do not vary across different locations but heavily depend on the wide coverage of transit services.

Table 7.27 The statistically significant variables in each of three cases

Case 1 (around Hankou Station)				
Trip modes[a]		B	Sig.	Exp(B)
Transit	Intercept	-4.260	.013	
	Distance	.343	.006	2.027
	[Gender=0]	1.017	.034	2.765
Driving	Intercept	-9.580	.006	
	Income	1.702	.001	5.484
	Distance	.706	.002	1.409
	Congestion	-1.214	.032	3.367
	[Gender=0]	3.417	.003	3.482
	[Purpose=1]	-2.612	.041	.073

Case 2 (around Wuchang Station)				
Trip modes[a]		B	Sig.	Exp(B)
Transit	Intercept	-8.330	.002	

	Distance	.936	.000	2.549
	Comfort	1.266	.019	3.547
Driving	Intercept	-10.456	.001	
	Number	2.134	.005	8.450
	Distance	.930	.000	2.535
	Economical	-1.529	.010	4.615

Case 3 (around Wuhan station)				
Trip modes[a]		B	Sig.	Exp(B)
Transit	Distance	.360	.038	1.433
Driving	Intercept	-7.433	.006	
	Income	1.626	.000	5.083
	Congestion	-1.217	.029	3.376
	Comfort	1.570	.028	.208
	Economical	-1.140	.047	3.127

Table 7.27 shows variables with statistical significance in the model from each case. In Case 1, the travelled distances and number of males have significance in the transit model. In contrast, factors such as family income, travelled distance, congestion level, number of males, and working purpose show effects in the driving model. In the Case 2, the factor of “comfort level” on travelling is in transit model rather than the factor “number of males” from Case 1. On the other hand, in the driving model, the additional factors such as car ownership, travelled distance, and economical level show significance in the model. Finally, in the Case 3, general factors such as family monthly income and three self-evaluation indicators show the influence of the driving model, while only travelled distance shows significance in the transit model. However, the common feature is that the variables such as “travelled distance” is in all transit models. For the driving model, indicators of self-assessment shared the same features in all driving model.

Due to data limitations, this study did not test whether there is significant travel mode preference associated with community type and size when the effects of socioeconomic factors and self-evaluation are controlled. Logistic regression analyses show that travel time and distance affect modes choice preferences when the effects of socioeconomic and self-evaluation factors are controlled. Rail-oriented development makes the non-motorised modes feasible.

7.4 Conclusions

This chapter quantitatively analyses the energy consumption from building clusters and transport-related carbon dioxide emissions due to the mobilities of users. The research examines selected factors related to energy demand from building clusters, which are street orientations, the layout of building clusters, overshadowing and UHI effects. Meanwhile, transport-related carbon dioxide emissions, including three aspects of socioeconomic factors, travel patterns, and self-evaluation, are also examined. The analysis in this research reveals the relationship between these selected factors and energy demand and associated carbon dioxide emissions from building clusters and transport. In addition, the analysis of the modelling helps to determine a better development path to reduce the energy consumption of buildings and carbon dioxide emissions of transport. The following parts are conclusions:

The impact of different variables on energy demand from building cluster:

(1) **Firstly, the least energy demand is in N-S street orientation (δ=0). Secondly, for the street orientation of δ=45 and δ=135, the heating demands are almost the same, which were also observed in the cooling demands, but their values are different. Finally, buildings in the E-W out of these four street orientations is the worst regarding energy consumption.**

(2) Building energy simulation on the layout of building cluster includes the ratio of Wy to Wx, ΔX to Wx, ΔY to Wy, and the building height differences (ΔH**). Firstly, the relationship between heating demand and the ratio of Wy to Wx is ambiguous**. It seems that the larger the ratio, the greater the heating demand. However, the highest cooling demand is needed when the ratio of Wy to Wx is either small or very large**. Secondly, the highest cooling demand occurs when the ratio of Δx to Wx is the largest, while this corresponds to the lowest heating demand. Thirdly, a positive effect is observed between the cooling demand and the ratio of ΔY to Wy. In contrast, there is a negative effect on the ratio of ΔY to Wy and the heating demand**. The lower the ratio, the higher the heating demand**. Lastly, energy demand fluctuates with building heights as well as solar gains**. For the cooling demand, the energy consumption is higher than the control group (uniform height), and a similar trend is also observed in the heating demand, but largely less than the control group when there is the height difference. **Moreover**,results also show that **building height differences can reduce the solar gains compared to the control group.**

(3) Based on the analysis of over-shadowing on energy demand, dense conditions can contribute to 4% of total building energy consumption and 23% reduction of solar gains compared to open conditions.

(4) Lowering the ambient temperature to relieve the heat island effects have been proved to reduce energy demand in buildings (Tarleton and Katz 1995). This study shows that the reduction of one-degree ambient temperature can contribute to saving around 3% of total building energy consumption.

It should be noted that these factors cannot be separately analysed on energy demand, especially relating to overshadowing and the layout of building clusters, because these factors have affected each other. For example, when given the ratio of Wy to Wx, although the ratio of Δ X to Wx is undefined, shading between buildings are affected, which is like the impact of the overshadowing on energy demand.

The impact of different factors on transport-related carbon dioxide emissions:

(1) According to the on-site survey from these three cases, transit modes are the most preferred travel modes.

(2) Travel time and travel distance are the primary factors of transit modes (metro and public transport), while family monthly income, car ownership, and self-assessment of travelling congestion and comfort level are the main influencing factors of driving modes (cars and taxis).

(3) For the increase of 1 km in travel distance, the likelihood of the option in transit modes is 1.113 times higher than driving modes. The probability of the choice on transit modes is 1.928 times greater than non-motorised modes (walking and cycling) when one minute of travel time increase.

Chapter 8 Conclusions, Limitations, Implications and Recommendations

8.1 Introduction

This chapter presents the conclusions of this research. Questions raised in Chapter one are answered, and the stated objectives are achieved. Implications of findings relating to strategies of low carbon city development are proposed regarding buildings and transport sectors. Finally, limitations and recommendations are discussed. Overall, this research not only presents a way to investigate the carbon dioxide emissions from an existing built environment relating to buildings and transport sectors but also gives practical suggestions for low carbon city development.

8.2 Conclusions

As discussed in Chapter 1, the aim of the research is:

"to investigate operational energy consumption and associated carbon dioxide emissions from building clusters and transport in order to reduce CO_2 emissions for low carbon city development".

The findings of this research are arranged into three aspects. The first is the method to understand, predict and analyse the energy performance and carbon dioxide emissions from buildings and transport sectors. The second is to examine and understand selected factors of low carbon city development in an existing built environment relating to buildings and transport sectors. Finally, the implications of findings include strategies to reduce CO_2 emissions in buildings and associated transport for low carbon city development.

8.2.1 Methods to predict energy consumption and associated carbon dioxide emissions

- **Technical tools used in this research are suitable, and research methods are reliable.**

For the building sector, this research presents an example of a bottom-up method based on three case study simulations. The research focused on building clusters, using the VirVil simulation tool for building energy simulation. This tool is able to consider the shading between buildings, which can lead to more accurate simulation. Measurements were available from the case study buildings, and these were used to compare with the simulation results, summarised in Table 8.1. For all three case studies, the simulation results were within a reasonable fit with the measured data.

Table 8.1 Building energy comparison between simulations and measurements among three Cases

<table>
<tr><th></th><th colspan="12">Simulations (kWh/year/m^2)</th><th colspan="12">Measurements (kWh/year/m^2)</th></tr>
<tr><td rowspan="2">Case 1</td><td colspan="3">Res.</td><td colspan="3">Commer.</td><td colspan="3">Office</td><td colspan="3">Hotel</td><td colspan="3">Res.</td><td colspan="3">Commer.</td><td colspan="3">Office</td><td colspan="3">Hotel</td></tr>
<tr><td colspan="3">113</td><td colspan="3">309</td><td colspan="3">140</td><td colspan="3">265</td><td colspan="3">85</td><td colspan="3">297</td><td colspan="3">116</td><td colspan="3">232</td></tr>
<tr><td rowspan="2">Case 2</td><td colspan="4">Res.</td><td colspan="4">Commer.</td><td colspan="4">Office</td><td colspan="4">Res.</td><td colspan="4">Commer.</td><td colspan="4">Office</td></tr>
<tr><td colspan="4">81</td><td colspan="4">320</td><td colspan="4">142</td><td colspan="4">53</td><td colspan="4">318</td><td colspan="4">120</td></tr>
<tr><td rowspan="2">Case 3</td><td colspan="6">Res.</td><td colspan="6">Commer.</td><td colspan="6">Res.</td><td colspan="6">Commer.</td></tr>
<tr><td colspan="6">90</td><td colspan="6">234</td><td colspan="6">62</td><td colspan="6">210</td></tr>
</table>

More specifically, for the Case 1, the range of the error is from 4% to 38%; for the Case 2, this range is from 0.6% to 50%, and 11% to 45% for the Case 3. These discrepancies generally agree with researchers Reinhart and Cerezo Davila (2016), where differences between measured and simulated results varied from 12% to 55% for urban scale studies. Moreover, the simulation results also agree with the statistics of the city government of Wuhan, which ranged from 92 to 134 kWh/ m^2 /year in residential buildings and 278 to 426 kWh/ m^2 / year in commercial buildings from the year of 2011 to 2016. Therefore, the method and technical tools used in building energy calculation were considered to be reliable.

For the transport sector, based on the literature review, there are only two methods for the calculation of transport-related CO_2 emissions. One is based on the total fuel consumption and emission factor, and the other is based on total travelled distance and emission factor. This research used the method based on travelled distance and emission factors to calculate associate transport CO_2 emissions. Meanwhile, this study used the non-fixed emission factors (annually decrease of 0.5%) based on the year 2006 to calculate the emission factors for the year 2016. This provides a better reflection of the real situations taking account of the advancement in fuel efficiency and vehicle technologies. Moreover, data collection of travelled distance is based on the investigation from respondents. Considering both aspects of non-fixed emission factors and real collected data of travelled distances provides a more accurate prediction of associated transport carbon dioxide emissions.

8.2.2 A better understanding of energy consumption and carbon dioxide emissions on building and transport sectors

- **Building energy simulation shows that there is the highest heating demand for residential buildings. By contrast, commercial buildings have the highest cooling demand. Therefore, reducing heating demand from residential buildings and cooling demand from commercial buildings should be considered.**

From the energy simulation of all three cases, the common features show that heating demand from residential buildings and cooling demand from commercial buildings were the highest. Case 1 exhibited the highest residential buildings heating demand of 68 kWh/m^2/year among the four building types, as well as the highest cooling demand of 129 kWh/m^2/year from commercial buildings. This similar feature (highest heating demand from residential buildings and highest cooling demand from commercial buildings) was also observed in Case 2 and Case 3 summarised in Table 8.2. The reasons for this are various. For residential buildings, the weather in Wuhan belongs to hot summer and cold winter, and one typical feature is that most people in domestic buildings use air-conditioning for heating in winter. Moreover, the heating efficiency is generally less than the cooling when air conditioning for heating purposes. For non-domestic buildings, especially for large-scale commercial buildings, the cooling demand is their primary energy consumption because these large-scale public buildings generally have a high occupant density. In addition, for non-domestic buildings, ventilation gains are also considered for cooling demand. These performances can help decision-makers, building designers, clients and researchers to understand the energy performance of buildings better, and thus energy-saving for buildings.

Table 8.2 Comparisons of cooling and heating demand among three Cases

	Heating demand (kWh/year/m^2)				Cooling demand (kWh/year/m^2)			
Case 1	Res.	Commer.	Office	Hotel	Res.	Commer.	Office	Hotel
	68	12	22	52	12	**129**	62	114
Case 2	Res.	Commer.	Office		Res.	Commer.	Office	
	37	23	16		11	**129**	70	
Case 3	Res.		Commer.		Res.		Commer.	
	33		24		11		**115**	

- A list of variables relating to street orientations, the layout of building clusters, overshadowing and UHI effects are simulated. **Results show that the least energy demand was in N-S street orientation, and the highest energy demand in E-S orientation; creating height difference among building clusters can reduce 8% of solar gains and save 2% of total building energy; the overshadowing in dense conditions shows that the solar gains can reduce 23% compared to the open conditions and can save 4% of total building energy; the reduction of one-degree ambient temperature on urban heat island effects can save to around 2% to 3% of total building energy.**

- Based on the investigation and the calculation of transport-related CO_2 emissions, results show that **transport-related carbon dioxide emissions by car and taxi are the primary sources of CO_2 emissions in all three cases.** In contrast, **transit modes have the lowest transport-related carbon dioxide emissions because of their low per capita carbon emission factors.** Moreover, the distribution of travel modes from three cases are compared by the investigation, and results show **transit modes are preferred, accounting for more than 50%.**

- Regression modelling analysis shows that **travel time and distance have**

statistical significance in relation to transit modes (metro and public bus). Moreover, family monthly income, car ownership and their travel self-assessment on congestion and comfort level are the driving forces for driving modes.

Based on the samples from three cases together, as travel time increases, people are more likely to choose transit modes than non-motorised modes (walking and cycling). The probability of the choice on transit modes is 1.928 times greater than the choice of non-motorised modes when an increase in one minute of travel time.

Meanwhile, the likelihood of the option of transit modes is 1.855 times higher than non-motorised modes for an increase of every 1 km of travel distance. Similarly, the probability of taking driving mode is 1.667 times greater than non-motorised modes when the trip distance becomes one kilometre longer. Because both odds ratios use non-motorised modes as the reference model; therefore, the odds ratio of taking transit over driving mode is 1.113 (1.855/1.667). This ratio means that when the trip distance increases in one kilometre, the likelihood of transit option is 1.113 times greater than driving modes.

Finally, the last conclusion answers the following question:

"How do transport-related carbon dioxide emissions relate to the building sector?"

- **Energy consumption and carbon dioxide emissions from building clusters are higher than those of transport-related CO_2, with the range of four to seven times.**

Based on the prediction of carbon dioxide emissions from buildings in Chapter 5 and the transport in Chapter 6, the comparisons are summarised in Table 8.3.

Table 8.3 Carbon dioxide emissions comparison between buildings and the transport

	Building carbon dioxide emissions (kg/m^2/year)	Transport-related carbon dioxide emissions (kg/m^2/year)	Residential building floor area (m^2)	Public building floor areas (m^2)
Hankou station	67	17	75073	84,006
Wuchang station	63	18	47476	126,042
Wuhan station	89	12	85256	180,000

Comparisons from Table 8.3 show that carbon dioxide emissions from buildings are higher than those of transport-related CO_2 emissions, with the range of from four to seven times. By comparison, the research from Lee et al. (2017), suggests that '*energy consumption of buildings (home and commercial) is two times higher than the transportation energy consumption (transport)*' in the city of Seoul. They state that the high energy consumption of buildings is continuously increasing if there are many high-rise buildings for the compact development in cities (ibid.). Moreover, the comparisons of CO_2 emission between buildings and the transport also indicate that to promote low carbon city development, the reduction of building energy consumption is the principal task.

8.3 Implications of findings for low carbon city development combining building and transport sector

Based on the conclusions of this study, strategies are given for low carbon city development, combining the building and transport sectors.

- **For the energy saving on building clusters, reducing gains, especially incidental gains for all buildings, are one of the strategies to save building energy. Furthermore, the focus on the reduction of heating demand from**

residential buildings and cooling demand from commercial buildings is another effective strategy to save energy.

Gains from buildings relating to solar gains, incidental gains, ventilation gains and fabric gains were analysed in all three cases. Meanwhile, features of building energy consumption from different building types were analysed. The results show that, on the one hand, incidental gains were dominant among all gains; on the other hand, most heating demands were on residential buildings, and cooling demand on commercial buildings. **Therefore, the reduction of incidental gains and heating demand is one way to reduce energy consumption for residential buildings, and the reduction of incidental gains and cooling demand for commercial buildings.**

- **For the reduction of transport-related carbon dioxide emissions, one method is to improve the percentage of the modal shift from private modes (car and taxi) to transit modes (public bus and metro).**

Based on the prediction of transport-related CO_2 emissions from three case, cars and taxis were the primary sources of CO_2 emissions, while the least transport-related CO_2 emissions were from transit modes due to the smallest emission factors. As a result, the percentage of private modes had powerful impacts on CO_2 emissions. Taking transport-related CO_2 emissions from residential buildings as an example, the largest CO_2 emissions were from Case 2 (614 kg/ year/capita), followed by Case 1 (557 kg/ year/capita) and Case 2 (426 kg/ year/capita). The intensity of transport-related CO_2 emissions is associated with the percentage of private modes of cars and taxis (Case 2: 23%, Case 1: 24%; Case 3:15%). **Therefore, improving the percentage of transit modes by providing the wide coverage of public transit nodes in the working and residential areas is one of the ways to reduce transport-related CO_2 emissions.**

- **For the reduction of transport-related carbon dioxide emissions, the locations, infrastructure and public services available can significantly affect transport-related CO_2 emissions.**

The level of urban development is significant to transport-related CO_2 emissions. Based on these three case studies, the location of Case 3 is in the new urban district and is at the initial development stage. Many public services and infrastructure are not available. Rail transits are not covered, and only public bus routes are available. In other words, many travel activities cannot be complete locally. However, the locations of Case 1 and Case 2 was outer and inner city and were better developed. Public services and infrastructures are provided, and many travel activities can be fulfilled locally. Carbon dioxide emissions from public buildings in Case 1 (391 kg/year/capita) and Case 2 (432 kg/year/capita) are noticeably less than those of from Case 3 (732 kg/year/capita). **Therefore, sufficient public services and infrastructure provided can reduce transport-related CO_2 emissions.**

- **Urban energy is consumed mostly by the transportation and building sectors. Base on the findings of the CO_2 emissions between the building and transport sector, the focus for low carbon city development should be on the building sector.**

All the conclusions and implications presented in this research can be the references for low carbon city development and then expand to the general situations. For example, for the reduction of transport-related carbon dioxide emissions, especially communities with the similar locations in the city: outer city, inner city, and new urban districts, these conclusions and findings can be duplicated to different projects across the country. For the building sector, these findings are directly applied to the reduction of building energy demand, especially among the hot summer and cold winter area, which is the same climatic conditions as Wuhan city.

8.4 Limitations of this study

This study aimed to predict carbon dioxide emissions from building clusters and the transport sector around the passenger railway stations, identify the relationship between energy consumption and selected factors, and propose strategies assisting in the reduction of urban carbon dioxide emissions. However, it must be admitted that there are limitations to this research, as discussed below.

Firstly, three cases are selected in one city rather than a nation-wide study. Although these three cases, in different locations, can represent a typical case for each one, the problems found in the cases may only be relevant in its specific contexts, such as different emission factors from various travel modes in different cities when considering the transport-related carbon dioxide emissions. Moreover, for building carbon dioxide emissions, weather conditions are closely related to energy demand, and this research only covers cold winter and hot summer zones, so this may lead to an inaccuracy in the building energy demand when applied in different weather zones. Therefore, some of the recommendations and strategies that are given in this research may not apply to the general context.

Secondly, it has been acknowledged that there are limitations to the self-evaluation on travel based on the survey from respondents, as the subjective evaluation by travellers may not represent a true assessment. The combination of subjective and objective evaluation can provide a more comprehensive and accurate assessment of travelling characteristics. Moreover, the lack of samples in this research may also lead to inaccuracy when doing regression analysis.

Thirdly, energy consumption and carbon dioxide emissions from building clusters exist in the life cycle, from the cradle to the grave. This research only considers the operational carbon dioxide emissions and neglects the embodied energy consumption, such as energy consumption from materials production and transport to the construction site. Therefore, this limitation can also lead to inaccuracy of the real situation.

Fourthly, due to the complexity and challenge of data collection, this research did not consider the interaction of travel activities between the study areas and the passenger railway stations, only considering the travel activities within the study area. As a result, it cannot analyse how the locations of railway stations affect the travel activities and thus transport-related carbon dioxide emissions.

Lastly, low carbon city development that focuses on a series of aspects (environmental, social, economic, and cultural) may lack certain elements in this study. This research mainly considers the environmental aspect from the elements of building and transport sectors, which is probably a deficiency in low carbon city development. The study was based on the professional perspective of carbon dioxide emissions in building clusters and the transport sector and adopted a building energy model consisting of different building types and activities-based transport demand model covering three categories by their carbon emission features. Due to the limited time, money, and complexity of data collection, this study had a comprehensive scope associated with low carbon city development from the aspects of urban and transport planning, yet it may overlook some issues related to low carbon, and lack depth in its discussions of the chosen issues.

8.5 Recommendation for future studies

Through the application of modelling in building clusters and transport sectors, this research has developed understanding of energy performance and carbon dioxide emissions of buildings and the transport sector around passenger railway stations. The following are some suggestions for future studies.

Firstly, the default setting of building energy modelling and travel activities in the transport are based on local, national statistics and on-site measurements. One possible reason for this is that this research aims to focus on the general situation in a city, not a specific building type or an area. However, for future studies, the variety of existing building types and related travel activities should be deeply understood and investigated, relating to construction ages, electricity usage, and travel patterns. Solid fundamental background information on buildings and transport sectors are not only helping to understand carbon dioxide emissions in specific areas clearly but also support future researchers on urban level situations and related strategies.

Secondly, the scope of this research does not cover all kinds of building in Wuhan and the building energy modelling only depicts the most general and typical building types. Therefore, aside from fundamental research to investigate related data on buildings, more simulations for specific building types and situations need to be discussed, such as community types and sizes. Moreover, the strategies for low carbon city development can be devised for various situations instead of one general situation.

Thirdly, technical tools should be improved continuously by considering more variables, particularly concerning microclimates. For the outdoor environment, to get more precise results and develop more strategies, there are other variables which should be calculated together, such as heat gains from urban heat islands and the transport.

Fourthly, for travel activities, it is better to consider the interaction of travel activities between the railway stations and the study areas. Moreover, small samples in this research can also lead to being inaccurate results, especially for transport-related carbon dioxide emissions. For the accurate calculation, it heavily based on sufficient samples and real data.

Lastly, the method applied in this research to predict carbon dioxide emissions from building clusters and the transport sector can be better integrated with the GIS system and then expanded to other critical issues such as social interaction and public health. These could further help to define the best solution for buildings and transport to reduce carbon dioxide emissions.

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