1 Introduction

§ 1.1 Background

The transition of the world population from a rural to an urban society has been a continuous and unstoppable process, which has characterized the world since the commencement of the Western European Industrial Revolution (Mumford, 1961). According to the United Nations (2014), the number of urban dwellers is expected to increase from 3.9 (in 2014) to 6.4 billion by 2050. In other words, about 65 million people are urbanizing every year, which is equivalent to the entire population of countries like France or the United Kingdom. One of the negative impacts of urban growth is climate change through the conversion of land uses (Meyer & Turner, 1992).

Sprawling cities and compact cities are the two most recognizable forms of urban growth (Jenks et al., 1996). The consequences of expanding cities through low-density suburbs is the increased dependence on automobiles, hence more consumption of fossil fuels and emission of greenhouse gases. In contrast, dense cities reduce the commuting distances from home to work, increase the viability of public transport and reduce the need for the spread of infrastructure networks due the concentration of different activities and diverse land uses (Thomas & Cousins, 1996). Although tall buildings are not the only solution to achieve high density, they are considered to be the best option for cities with limited land available for expansion (Yuen, 2005). In addition, high-rise buildings can accommodate more people on the same land than low-rise buildings. A smaller footprint by going upward leaves more space for parks and green spaces, which is an effective way to reduce the urban heat island effect.

The main driver for tall building development, however, can be addressed by its positive socio-economic benefits. Limited land and increasing prices, mature economies and the desire for global competition are important reasons for the increased construction of tall buildings (Watts, 2013). Nowadays, new plans for the densification of urban sites and implementation of new tall buildings are found all around the world, including North-American cities such as Chicago and New York, European cities, such as London, Paris, Frankfurt and Rotterdam as well as Southeast Asian cities such as Singapore, Kuala Lumpur and Bangkok. Despite the positive contribution that tall buildings can have for sustainable development, conventional tall (office) buildings have a greater

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environmental load (Dobbelsteen, 2012; Dobbelsteen et al., 2007) and they consume more energy per square meter than low-rise (office) buildings (Lam et al., 2004).

§ 1.2 Definition

There are many definitions for high-rise buildings that consider their height, number of stories and their usage (see Table 1.1). The Council of Tall Buildings and Urban Habitats (CTBUH, 2014) defines a high-rise as: "A building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period". For instance, a relatively small building may be considered a high-rise if it stands well above its built environment and changes the overall skyline. The maximum height of structures has progressed historically with building methods and technologies and thus what we today consider a high-rise is taller than before. According to CTBUH, a building that is over 14 stories (or more than 50 m in height), can be classified as a tall building. They further sub-divided tall buildings with significant height to supertall and megatall, which refers to buildings that are over 300 m and 600 m in height respectively. This research focuses on commercial forms of high-rise buildings that are between 50 to 300 m in height.

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SOURCE	HIGH-RISE BUILDING	SKYSCRAPER
Britannica Concise Encyclopedia	Multi-story building tall enough to require the use of a system of mechanical vertical transportation such as elevators.	The skyscraper is a very tall high-rise building. The term originally applied to buildings of 10–20 stories, but now generally describes high-rises of more than 40–50 stories.
McGraw-Hill Dictionary of Architecture and Construction	A building having a large number of floors, usually constructed where land costs are high.	A very tall, multi-storeyed building, usually having curtain walls, so that the exterior walls are non-load-bearing, being supported independently at each floor by its skeleton-frame construction.
The American Heritage Dictionary of the English Language	Indicating or being a multi-storeyed building equipped with elevators.	
Wikipedia	A high-rise, tower block, apartment tower, office tower, apartment block, or block of flats, is a tall building or structure used as a residential and/or office building. In some areas they may be referred to as "MDU" standing for "Multi Dwelling Unit". These buildings are considered shorter than skyscrapers.	A tall, continuously habitable building of many stories, usually designed for office and commercial use. There is no official definition or height above which a building may be classified as a skyscraper though a building lower than about thirty stories is not likely to be a skyscraper and a building with fifty or more stories is certainly a skyscraper.
Emporis Standards	A multi-story structure between 35-100 meters tall, or a building of unknown height from 12-39 floors.	A multi-story building at least 100 meters tall.
Oxford English Dictionary	A tall modern building containing numerous floors of offices or flats (=tower block).	A very tall building of many stories.
United States General Laws (Salankar et al., 2016)	A building higher than 70 feet (21 m).	
Collins English Dictionary	A high-rise is a modern building which is very tall and has many levels or floors (=skyscraper, multi, multi-story).	A very tall multi-storey building (=tower).
Ken Yeang (1999)		The term skyscraper is used (in his book) as a convenient abbreviation for the large high-rise intensive building type, generally regarded as being over 10 stories and which can be of commercial, residential, hotel or mixed used.

TABLE 1.1 Definition of high-rise building and skyscraper.

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§ 1.3 Problem statement

From the first generation of high-rise buildings in North America up to the present day, the architectural design of tall buildings has undergone a number of changes, influenced by regional regulations, new technologies and the worldwide energy crisis (Gonçalves, 2010). Historically, architectural forms followed passive design solutions to provide desirable internal conditions. From the 1950s, air conditioning became a key element in high-rise office design, enabling architects to test new design opportunities (i.e. curtain wall and deep plan), as a result of which the external climate conditions were no longer a limiting factor that influenced the design (Fenske, 2013). The formation of sealed glass boxes with deep floor plates increased the dependency of tall office buildings on air conditioning and artificial lighting. This model of high-rise typology became the representative of an international style of the modern movement and of economic wealth and spread throughout the world regardless of climatic and contextual differences.

With the emergence of the energy crisis in the 1970s, and following that, the rise of an environmental consciousness in the 1980s and 1990s, energy-saving measures and sustainable buildings became a topic of attention (Gonçalves, 2010). In response to increasing global pressure for improving the environmental performance of buildings, the European Union suggested a roadmap to cut the CO_2 emissions from houses and office buildings by around 90% below 1990 levels by 2050 (European Commision). In line with that, many green building assessment systems have been established globally, with the aim to encourage the construction market to develop greener buildings with lower energy consumption. In spite of the advances in the construction industry and the raising awareness of the contribution of the building sector to climate change and global warming, the question arises why there are few built examples of well-performing tall buildings – even the Commerzbank building, considered an ecological high-rise, had a higher environmental load than low-rise alternatives (Colaleo, 2003) – and why there is little interest to release the operational data of such buildings into the public domain.

The common criticism is associated with poor architectural design, which makes tall buildings intense energy consumers. In order to have high-performance tall buildings, first there is a need to reduce the building's demand for energy and the most straightforward approach is to design them in a way that reduces their appetite for energy. However, energy-efficiency is often demonstrated by high-performance appliances and technologies (e.g. lighting, HVAC systems, and elevators) rather than the design in the first place. For building projects for which the architectural design is not optimally treated as an integral part of environmental design at the outset of a project, the potential for energy saving is limited. Increasing the awareness about the importance of architectural design strategies for reducing the energy use in buildings can limit the number of ineffective designs.

Furthermore, an environmentally responsive architecture can add value beyond what energy saving could offer. The Green Building Council Austrlia (2006) identified key economic benefits that green buildings could deliver to building developers, owners and tenants (see Table 1.2). Market differentiation, improved return on investment, higher occupancy rate, and increased staff productivity are among the benefits that green buildings can offer. In another study, the results of annual expenses breakdown for a group of typical commercial buildings in North America showed that staff salaries dominantly outweighed other costs including those involved with the maintenance (1%), utilities (1%), taxes (1%) and rent (9%) (Lucuik et al., 2005). This indicates that a small increase in productivity can have large economic benefits. A Californian study found that up to 20% improvement in staff performance can be achieved through enhancing the physical comfort conditions of indoor environment including daylight, ventilation, view and temperature. Therefore, the benefits of environmental design are numerous and of paramount importance and they outweigh the increased initial costs and reduced lettable floor area that is typically associated with designing well-performing commercial buildings (Eichholtz et al., 2013).

FOR BUILDING DEVELOPERS	FOR OWNERS/OCCUPANTS
Enhanced ability to rent or sell building	Improved public image
Improved occupancy rates: 3.5% higher	Up to 60% reduction in water and energy consumption
Higher rents: 5-10% increase	Superior thermal, indoor air and lighting quality
Increased asset value: 10% increase	Increased occupant satisfaction and productivity: up to 25% annually
Improved return on investment: minimum 14%	

TABLE 1.2 Economic benefits of using an environmental design as opposed to a conventional design for commercial buildings. Adapted from (Green Building Council Australia, 2006).

§ 1.4 Research objectives

The principal objectives of this dissertation are:

- to explore the impact of architectural design strategies on energy consumption and thermal comfort of tall office buildings in temperate, sub-tropical and tropical climates
- and based upon these results, to develop recommendations for high-rise office building design in temperate and tropical climates to support designers in the decision-making process

§ 1.5 Boundary conditions

Comparing the Köppen-Geiger climate classification world map with a map showing the distribution of high-rise buildings around the globe, it can be observed that the majority of high-rise buildings have been constructed in cities with temperate, sub-tropical and tropical climates. The outdoor air temperature in sub-tropical climates is close to the comfort temperature of humans throughout the course of the year so that the required energy for space conditioning is typically lower than in the other two climates. Furthermore, the results of energy simulations confirmed this claim because the impact of architectural design strategies on building energy use was lower in absolute value. Furthermore, the majority of design strategies that was found to be effective for the building envelope in the tropical climate can be used with only minor changes for the sub-tropical climate. For this reason, the sub-tropical climate will not be thoroughly discussed in this dissertation and the area of investigation is mainly limited to certain design strategies that may have a greater impact on energy use such as geometry factors (chapter 3). As a result, the main focus of this research and the development of design recommendations will be for two climates −namely temperate and tropical− in which the design could have a greater influence on building energy use.

In this research, the focus of investigation is on one particular form of buildings, the high-rise office typology, which is believed to reflect a higher concern. Recent studies showed that the commercial sector, and in particular the office sub-sector, offers the greatest potential for energy saving as it is a significant contributor to energy use and carbon emissions (Wade et al., 2003). From the commercial perspective, office buildings offer higher returns than other types of properties, so the risk of investment is lower and therefore there is a greater desire for investing in innovative design strategies among building developers and building owners (Green Building Council Austrlia, 2006). Besides, the integration of passive design techniques into an office building could be more challenging for designers (due to larger floor plate depths, higher internal gains, higher lighting demand and the special arrangement of internal spaces); hence, further study is needed on this topic.

Apart from that, the high-rise typology is different from the low-rise one in terms of the influential parameters that affect the building performance so that the design should be tailored to the specific requirements of high-rises. An increase of the building height can induce the stack effect which increases the amount of infiltration and heat loss through the building façade. This can possibly influence the optimal size of openings and the insulation properties of the envelope. On the positive side, the excessive height can be used to assist natural ventilation using vertical shafts. Another difference that can cause design differences is related to climatic parameters that change with height. With the increase of the building height, the air temperature tends to slightly drop and the wind speed get higher. As a result, the upper floors may need lower amounts of cooling energy in summer but higher amounts of heating energy in winter as compared to the base floors. The high wind speed and difficult accessibility, in addition, may limit or make unfeasible the application of certain design elements. Considering the urban context, the building form and orientation should be adjusted according to adjacent buildings, as they can influence the solar gains and wind flow patterns to a large extent. The residents of conventional tall buildings have a stronger feeling of being disconnected from the outside environment which may affect their productivity and well-being. The amount of internal gains is higher in high-rise buildings, which can influence the amount of energy use for cooling and heating compared to their mid- or low-rise equivalents. A higher percentage of space should be allocated to the circulation spaces and structural components which can result in lower space efficiency. For effective daylighting and natural ventilation, certain design elements are required; however, fire safety regulations should be addressed as well. All these factors indicate the importance of this particular building typology, so that further investigation is required.

The main aim of this research is to reduce the energy demand of tall office buildings through architectural design. To achieve high levels of energy-saving, however, it is important to acquire a good understanding of how architectural design strategies can influence the total energy use (and different energy end-uses) individually and as a group. Energy simulations, if well-validated, can help us to correctly apply design strategies to achieve considerable energy-savings.

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§ 1.6 Research questions

Main question

Following these objectives, the main research questions are formulated as:

- To what extent do architectural design strategies affect energy consumption of and thermal comfort in high-rise office buildings in temperate, sub-tropical and tropical climates?
- What design factors should be focused on during the decision-making process to achieve a high-performance design in temperate and tropical climates?
- In order to properly address the main research question, the following background and sub-questions need to be answered:

Background questions

Q.1a: What is the best method to quantify the impact of architectural design strategies on energy consumption and thermal comfort of high-rise buildings?
Q.1b: How can architects benefit from the results of this study for improving the performance of high-rise office buildings?

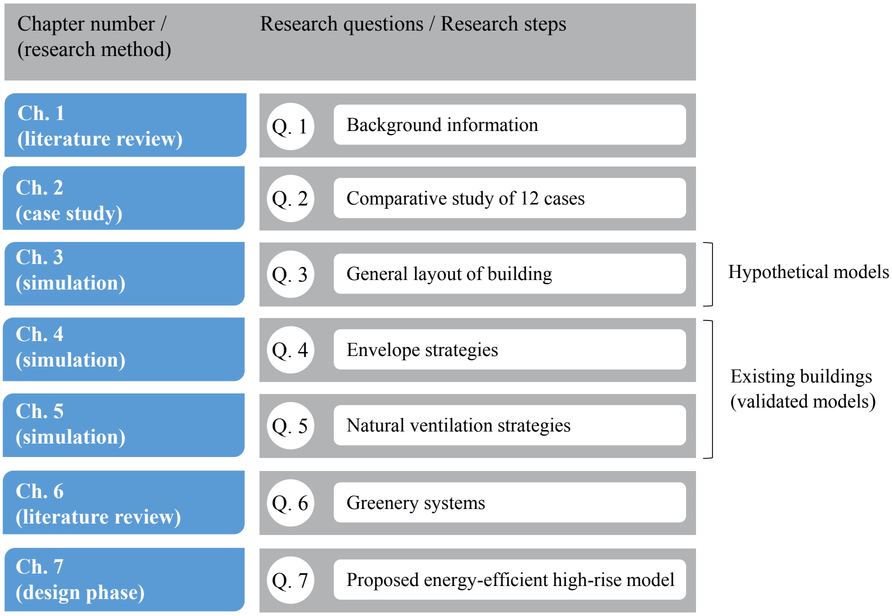
Sub-questions

Q.2: What are the design differences between a typical and sustainable high-rise office buildings in temperate, sub-tropical and tropical climates?
Q.3: To what extent do geometric factors affect the energy-efficiency of high-rise office buildings?
Q.4: To what extent do envelope design strategies affect the energy-efficiency of high-rise office buildings?
Q.5: To what extent do natural ventilation strategies affect energy-efficiency of and thermal comfort in high-rise office buildings?
Q.6: To what extent do greenery systems affect the energy-efficiency, thermal comfort and indoor air quality of high-rise office buildings?
Q.7: What are the essential architectural design features for high-rise office buildings' energy-efficiency in temperate and tropical climates?

§ 1.7 Research method

§ 1.7.1 Research steps and approaches

The main focus of this research is to assess the performance of architectural design strategies for energy-efficiency of tall office buildings, and based on these results, develop recommendations for designers of high-rise office buildings in temperate and tropical climates. This dissertation implements three data collection methods to address the research objectives and questions: a) literature review, b) case study, c) simulation-based performance analysis. Afterwards, a summary of the recommended design strategies is provided for temperate and tropical climates. Finally, through a design phase, a three-dimensional model of an energy-efficient high-rise office building is suggested for each of the two climates. The schematic representation of research steps and approaches is presented in Figure 1.1.



Chapter number / (research method)	Research questions / Research steps		
Ch. 1 (literature review)	Q. 1	Background information	
Ch. 2 (case study)	Q. 2	Comparative study of 12 cases	
Ch. 3 (simulation)	Q. 3	General layout of building	Hypothetical models
Ch. 4 (simulation)	Q. 4	Envelope strategies	Existing buildings (validated models)
Ch. 5 (simulation)	Q. 5	Natural ventilation strategies	
Ch. 6 (literature review)	Q. 6	Greenery systems	
Ch. 7 (design phase)	Q. 7	Proposed energy-efficient high-rise model	

FIGURE 1.1 Scheme of research steps and methods, and the connection with main research questions.

a) To address two research questions (Q.1 and Q.6), data and information was merely gathered through a literature search. The introduction chapter provides some background information about the evolution of high-rise buildings and the key factors affecting their design historically. Later on, chapter 6 provides an in-depth literature review for different greening systems with respect to their energy impact. For two reasons the literature search was selected among other methods to investigate the contribution of greenery systems on energy-saving. Firstly, a simulation tool that can accurately calculate the evapotranspiration and shading effect of vegetation together and for both of the vertical and horizontal greening systems was not available at the time of investigation. Secondly, the results of previous experimental studies showed the extent of energy saving from the application of greenery systems is very limited compared to other strategies (related to architectural design), therefore does not merit further experimental investigation. However, other large-scale benefits for the urban environment (mitigation of CO_2 concentration) and building residents (increased productivity and higher well-being) could justify the application of greenery systems as an essential sustainability feature for the design of tall office buildings. As a result, chapter 6 is allocated to the study of different greenery systems (in terms of energy-saving, indoor air quality, thermal comfort and other factors) through a review of past research.

b) In order to address the design differences between a typical and a sustainable high-rise office building (Q.3), twelve case buildings were selected with different degrees of sustainability performance, from three climate types (temperate, sub-tropical & tropical). For each climate group, there were three sustainable high-rises and one typical high-rise design as a reference. Building-related energy performance data were collected through contact with the energy consultants involved in the respective building and using data from secondary (literature) sources. The total energy use (and different energy end-uses) of each group of buildings in one climate (four cases) were compared together, and also with the energy benchmarks, to analyse the effectiveness of different design strategies in the specific climate type. Comfort requirements of different climates/cases and the impact that they might have on energy use were discussed as well. Finally, lessons from these buildings were defined for the three climates. Design strategies under four categories were identified for further investigation including: (1) geometric factors, (2) envelope measures, (3) natural ventilation, and (4) greenery systems. For the first three categories, simulation-based studies were conducted, while for the last one, a literature review was done.

c) Simulation studies (CFD studies, parameter studies and sensitivity analyses) were carried out to quantify the impact of geometric factors (Q.4), envelope elements (Q.5) and natural ventilation strategies (Q.6) on building energy performance and thermal comfort by using hypothetical building models or existing buildings. The DesignBuilder (version 3.4 and 4.7) interface for EnergyPlus was used as a performance assessment tool. For the investigation on building general layout, hypothetical building models (40-storey) were incorporated in three climate contexts: Amsterdam (temperate), Sydney (sub-tropical) and Singapore (tropical). However, for the investigation of envelope elements and natural ventilation strategies, existing tall office buildings were selected as typical high-rise designs in temperate and tropical climates; these were modelled in DesignBuilder. The EWI building (21-storey) in Delft, the Netherlands, was selected as the representative for the temperate climate and the KOMTAR tower (65-storey) in George Town, Malaysia, for the tropical climate. The models of these buildings in DesignBuilder were validated by comparing measured and simulated annual and monthly energy use intensity (EUI) of the buildings for one year. The measured data were obtained from the literature in case of the KOMTAR tower or from the building management in case of the EWI building.

In chapter 5, the potential use of natural ventilation (NV) strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings was investigated by using the same validated base models from chapter 4. The investigation of natural ventilation (NV) strategies comprised of two main steps: (1) the study of the impact of natural ventilation strategies on indoor comfort indicators including thermal comfort and fresh air during the operation of natural ventilation by using EnergyPlus; and (2) the study of the indoor air temperature and the velocity contours under different weather scenarios (during typical and extreme weather conditions) by using Computational Fluid Dynamics (CFD). Further details on the methodology will be provided in each respective chapter.

§ 1.7.2 Simulation tool

There is common agreement that: “building performance simulations are an integral part of the design process for energy-efficient and high-performance buildings, since they help in investigating design options and assess the environmental and energy impacts of design decisions” (Aksamija, 2012, p. 1). There is an increasing number of simulation tools available, capable of running complex calculations by using rigorous approaches. In all energy simulations, there are four main steps that needs to be performed; creation of the model, setting up inputs, validation of the model, and analysis of results. DesignBuilder’s fully-integrated approach provides this possibility to develop one core model and use it to run a variety of assessments using different engines (EnergyPlus and CFD). The intuitive structure allows to run simulations for large complex buildings with minimum tendency to crash. The well-structured

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graphical interface and data management tools of DesignBuilder make it a much easier tool for building simulation users, while the power and flexibility of EnergyPlus, the underlying simulation engine, enhances the reliability of results.

Energy calculation

As a result, the DesignBuilder interface for EnergyPlus was used as a building energy performance simulation tool to create the models. DesignBuilder is a validated tool that has passed Building Energy Simulation Tests (BESTest) according to the ISO 13790 (2008) standard for the calculation of energy use for space heating and cooling and the ANSI/ASHRAE Standard 140 (2011) for building thermal envelope and fabric loads.

Computational Fluid Dynamics (CFD)

The air flow rate and the temperature distribution in the building were simulated with the help of CFD. In this study, the CFD code from DesignBuilder was employed. The most widely used and tested turbulence model, k-ε turbulence model, was selected which belongs to the RANS family of models. The DesignBuilder's CFD code has been validated by a number of studies through a comparison with measured data from existing buildings (Baharvand et al., 2013; Chung et al., 2014) and also in comparison with the generated results from other CFD packages (Northumbria University, 2011). Using the CFD package in DesignBuilder simplifies the input of boundary conditions, since there is the possibility of using previously calculated quantities of temperatures, heat flows and flow rates from the airflow network model in EnergyPlus.

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§ 1.8 Research outline

The schematic representation of the dissertation outline is presented in Figure 1.2.

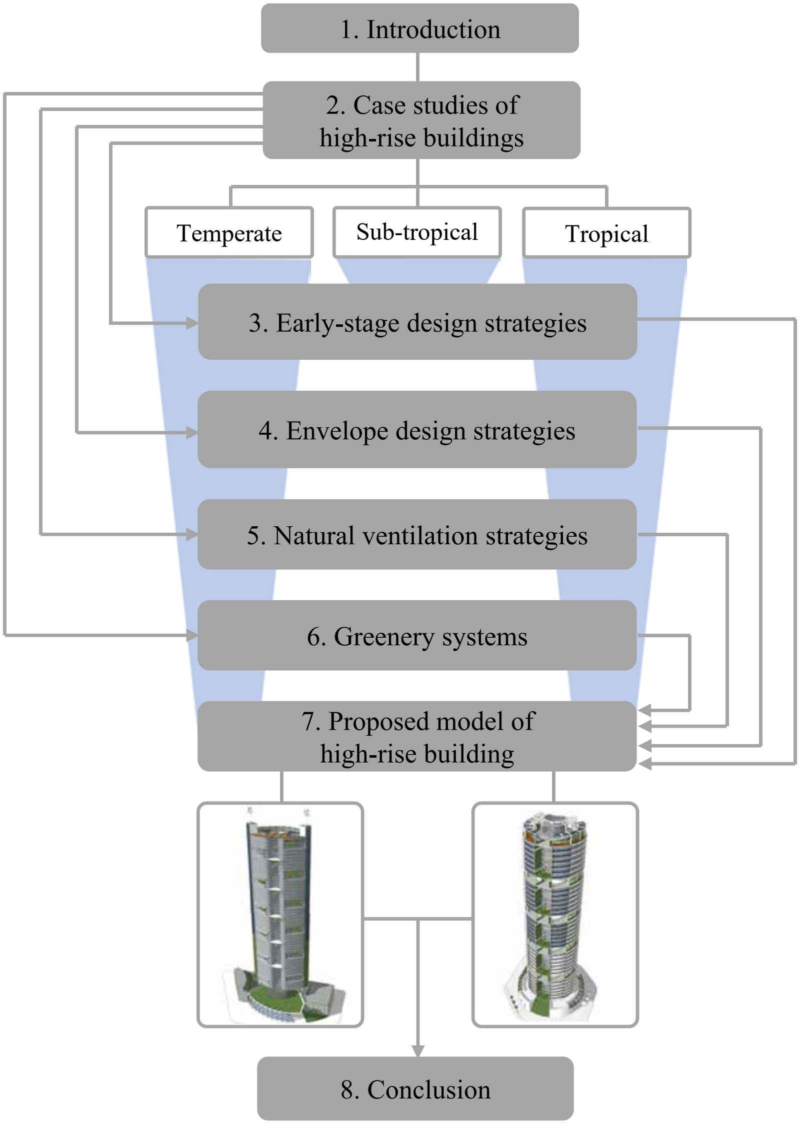

FIGURE 1.2 The outline of dissertation.

Chapter 2) On the basis of a case-study approach with multiple cases (12 case buildings), chapter 2 compares the effectiveness of implemented design strategies between high-performance (sustainable) and low-performance (conventional) existing examples of high-rise buildings in three climates; temperate, sub-tropical and tropical. The energy data of each group of buildings in one climate (four cases) is collected to analyse the effectiveness of different design strategies in the specific climate type. Furthermore, a comparison with international benchmarks shows the effectiveness of design strategies for each climate. This research showed which design strategies are more effective for sustainable high-rises to reduce the energy consumption for cooling, heating, ventilation and lighting and which ones should be avoided (based on the reference conventional examples).

Chapter 3) Decisions made at early stages of the design are of the utmost importance for the energy-efficiency of buildings. Using extensive parametric energy simulations, chapter 3 investigates the impact of geometric factors for the energy-efficiency of high-rise office buildings in three climatic contexts: Amsterdam (temperate), Sydney (sub-tropical) and Singapore (tropical). The investigation is carried out on 12 plan shapes, 7 plan depths, 4 building orientations and discrete values for window-to-wall ratio, using hypothetical models of tall buildings with a total floor area of 60,000 m^2 distributed over 40 storeys with identical floor plans.

Chapter 4) The building envelope is the interface between the interior of the building and the outdoor environment. A building’s energy consumption to a large extent depends on certain envelope design elements. Chapter 4 aims to find energy-saving solutions for the envelope design of high-rise office buildings in temperate and tropical climates. For this purpose, an existing tall office building is selected as a typical high-rise design in each of the two climates and the energy use prior and after refurbishment is compared through computer simulations. By taking the base case as a reference and optimising one parameter at each step, this study resulted in a high-performance envelope design that offers a considerable energy-saving.

Chapter 5) Chapter 5 investigates the potential use of natural ventilation strategies to reduce the energy demand for cooling and mechanical ventilation for high-rise buildings. Different natural ventilation scenarios are developed for the base design (using the same validated base models from previous chapter) and the CFD package in DesignBuilder is used to predict air velocity and temperature distribution under different weather conditions. The operative temperature and the total fresh air changes per hour are calculated with EnergyPlus and are compared accordingly with the local comfort standards. The percentage of discomfort hours indicates when a ventilation system would need active cooling or mechanical ventilation. In tropical climates, the potential benefits of elevated velocities for improving thermal comfort is additionally investigated.

Chapter 6) Greenery systems are among the essential sustainability features for the environmental design of tall buildings. Chapter 6 provides a literature review on different greenery systems and the potential energy benefits that they can offer to a building. Furthermore, the suitability of different greenery systems for different climate types is discussed.

Chapter 7) Chapter 7 consolidates the findings from previous chapters to point out general and climate-specific design strategies that are required for energy-efficiency of tall office buildings. The outcomes will be used by the end of this chapter to illustrate a proposal for an energy-efficient high-rise office building in the temperate and tropical climates.

Chapter 8) Finally, the main highlights and recommendations are concluded in chapter 8.

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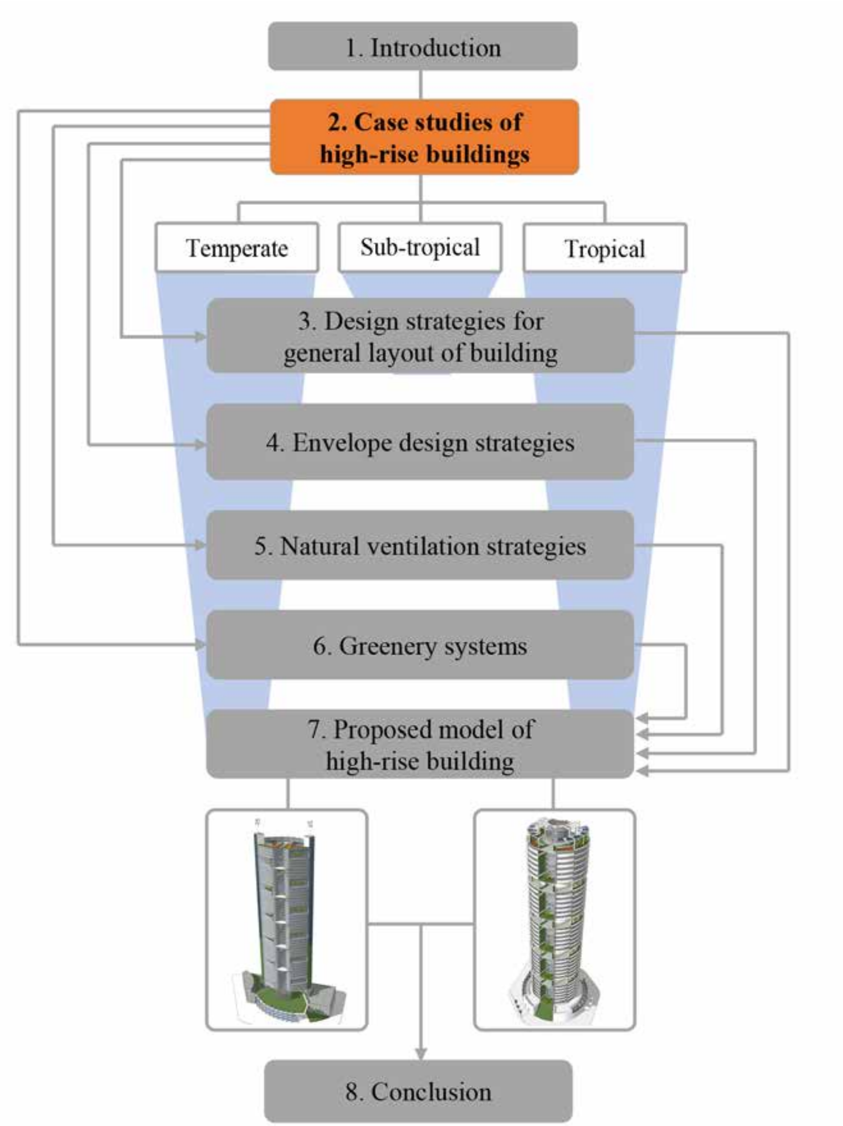
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