Dissertation

Office Space Design for Flexibility: An Approach to Guarantee Thermal Comfort During the Entire Operation Phase

Jasmin Anika Gärtner

TECHNISCHE UNIVERSITÄT MÜNCHEN

Fakultät für Architektur

Lehrstuhl für Gebäudetechnologie und klimagerechtes Bauen

Office Space Design for Flexibility: An Approach to Guarantee Thermal Comfort During the Entire Operation Phase

Jasmin Anika Gärtner

Vollständiger Abdruck der von der Fakultät für Architektur der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

Vorsitzender:	Prof. Florian Nagler
Prüfer der Dissertation:	1. Prof. Thomas Auer
	2. Prof. Dr.-Ing. Frank Petzold

Die Dissertation wurde am 05.08.2020 bei der Technischen Universität München eingereicht und durch die Fakultät für Architektur am 29.01.2021 angenommen.

Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als Doktorandin in der Gruppe für Gebäudesysteme in der zentralen Forschung der Robert Bosch GmbH, Renningen, und in Zusammenarbeit mit dem Lehrstuhl für Gebäudetechnologie und klimagerechtes Bauen an der Fakultät für Architektur der Technischen Universität München.

Ich möchte mich an dieser Stelle bei allen bedanken, die mich während dieser Zeit unterstützt und damit zum Entstehen dieser Arbeit beigetragen haben:

Zunächst bedanke ich mich besonders bei Prof. Thomas Auer für die Betreuung meiner Arbeit und für die Unterstützung während der Zeit meiner Promotion. Ich habe unsere Besprechungen als große Bereicherung empfunden und bin dankbar dafür, dass er immer genau die richtigen Fragen gestellt hat, um meine Forschung voranzutreiben.

Bei Prof. Dr.-Ing. Frank Petzold bedanke ich mich ebenfalls für seine fachliche Unterstützung.

Ein großer Dank gilt Dr.-Ing. Francesco Massa Gray, meinem Betreuer bei der Robert Bosch GmbH. Er hat mich in den letzten Jahren immer unterstützt, meine Visionen und Ideen geteilt und mich immer wieder herausgefordert meine Forschung zu hinterfragen. Vielen Dank auch für die vielen wertvollen Diskussionen und die Korrektur meiner Texte. Ich hätte mir keinen besseren Betreuer vorstellen können.

Vielen Dank auch an meinen Gruppenleiter Dr.-Ing. Philipp Kotman für die Diskussion meiner Ideen und die Unterstützung meiner persönlichen Entwicklung. Unsere Rücksprachen waren für mich immer sehr wertvoll und inspirierend. Außerdem möchte ich dem gesamten CR/AEB-Team und insbesondere meinen Kollegen Torsten Welfonder, Thomas Makowicki, Dr.-Ing. Sebastian Martens, Dr.-Ing. Fabian Schmid, Dr.-Ing. Jan Gall, Guillaume Huard und Dr.-Ing. Valentin Schwamberger, für die interessanten Diskussionen, technische Unterstützung, herausfordernden Fragen und unterstützenden Worte danken. Ein besonderer Dank geht an die AEB-Doktoranden Stephanie Kaschewski, Tim Jourdan und Alexander Koch für ihre moralische Unterstützung. Vielen Dank auch an meinen Mentor Martin Windhab für die wertvollen Kontakte und Einblicke in die Baupraxis. Mein Dank geht auch an mein Studententeam Jan-Lukas Gehl und Martin Gabriel, die zu dieser Arbeit beigetragen haben.

Darüber hinaus danke ich Christian Frenzel für seine technische Unterstützung bei allen Fragen zu TRNSYS und für die wertvollen Diskussionen.

Vielen Dank auch an alle Mitglieder des TUM-Lehrstuhls für Gebäudetechnik und klimafreundliches Design für die Fragen und Diskussionen zu meiner Forschung.

Ein besonderer Dank geht an meine Familie und meine Freunde, besonders an meine Eltern Ute und Josef und an meinen Bruder Adrian, die mich immer unterstützt und an mich geglaubt haben. Außerdem danke ich meinem Opa Franz, dass er mir schon als Kind die Welt erklärt und damit den Forschergeist in mir geweckt hat. Und nicht zuletzt ein besonderer Dank an meinen Mann Fabian für seine Unterstützung in allen Phasen meiner Dissertation. Er hat mich während dieser intensiven Zeit immer wieder bestärkt, mir Mut zugesprochen, mit mir Ideen gesponnen und musste sich so manche meiner wilden Theorien anhören. Ohne dich hätte ich es nicht geschafft.

"WE SHAPE OUR BUILDINGS
AND AFTERWARDS OUR BUILDINGS SHAPE US."

- *WINSTON CHURCHILL (1943)*

Abstract

As people spend most of their lifetime in buildings, maintaining comfortable indoor climate conditions is of major importance. For this purpose, heating, ventilation and air conditioning (HVAC) systems are used in office buildings to regulate the indoor climate. In order to ensure a satisfactory performance, they must be adapted to the prevailing conditions in the office space. This can be challenging, because the HVAC system design is typically defined during the conceptual design phase when the space layout design and the office usage are not known exactly. Moreover, during the operation phase of an office building, its space layout design is changed every 3–7 years. Thus, in order to maintain comfortable indoor climate conditions and guarantee that the HVAC systems are operated in an energy-efficient way, both the HVAC system configuration and its control zoning strategy need to be flexible. Considering this situation, the research questions dealt with in this dissertation are: *“How can a flexible office space design be enabled during the entire operation phase of an office building, without compromising on thermal comfort or energy-efficiency?”* and *“What are the relevant flexible design parameters to consider in design decisions and which configurations of these parameters enable a flexible office space design?”.*

In the reviewed literature, the correlation between the space layout and the HVAC system design has not been investigated in detail. However, available results indicate an untapped potential for creating robust solutions for flexible office spaces. In this work, an approach to evaluate this flexibility is developed. The approach considers the space layout design, the HVAC system configuration and its control zoning strategy as *flexible* design parameters and evaluates their individual influence on thermal comfort and energy efficiency in detail. In addition, it is applied to a modern office space through an extensive simulation study. The results indicate that radiant ceilings and thermally-active building systems (TABS) are promising solutions for flexible office spaces, whereas mechanical ventilation systems require a more complex control strategy to ensure thermal comfort. Finally, recommendations for the realization of an *office space design for flexibility* are presented to support design decisions during the conceptual design or interior renovation phase. In conclusion, this dissertation demonstrates that the mentioned flexible design parameters cannot be considered independently to create robust solutions for office spaces: Only a comprehensive understanding of their correlations can enable a holistic office space design for flexibility.

Kurzfassung

Da Menschen die meiste Zeit in Gebäuden verbringen, ist die Gewährleistung eines komfortablen Raumklimas von großer Bedeutung. Aus diesem Grund werden in Bürogebäuden Heizungs-, Lüftungs- und Klimatechnik (HLK)-Systeme eingesetzt, um das Raumklima zu regulieren. Diese müssen jedoch an die vorherrschenden Bedingungen im Raum angepasst werden. Das kann eine Herausforderung darstellen, da diese Systeme üblicherweise in der Konzeptphase definiert werden, in der das genaue Raumlayout und die Nutzung des Büros noch nicht bekannt sind. Außerdem wird das Raumlayout während der Betriebsphase ungefähr alle 3–7 Jahre geändert. Um trotzdem ein komfortables Raumklima und einen energieeffizienten Betrieb zu gewährleisten, müssen sowohl die HLK-Systeme als auch deren Zonierung flexibel sein. In Anbetracht dessen werden in dieser Dissertation die folgenden Forschungsfragen untersucht: *„Wie kann eine flexible Gestaltung von Büroflächen während der gesamten Betriebsphase ermöglicht werden, ohne dass der thermische Komfort und die Energieeffizienz beeinträchtigt werden?“* und *„Welches sind die in der Planung relevanten flexiblen Parameter und welche Konfigurationen ermöglichen diese Flexibilität?“*.

In der Literatur wurde der Zusammenhang zwischen Raumlayout und HLK-Systemen nicht ausreichend untersucht. Trotzdem kann man aufgrund von vorhandenen Ergebnissen auf ein ungenutztes Potential zur Entwicklung von robusten Lösungen für flexible Büroflächen schließen. In dieser Arbeit wird eine Methode entwickelt, um diese Flexibilität zu beurteilen. Dabei werden das Raumlayout, die HLK-Systeme und deren Zonierung als *flexible* Parameter modelliert, um deren individuellen Einfluss auf den thermischen Komfort und Energieverbrauch zu beurteilen. Darüber hinaus wird diese Methode in einer umfangreichen Simulationsstudie auf ein modernes Bürogebäude angewendet. Die Ergebnisse zeigen, dass Heiz-/Kühldecken und eine Bauteilaktivierung vielversprechende Lösungen darstellen. Wohingegen mechanische Lüftungssysteme eine komplexere Regelungsstrategie erfordern, um den thermischen Komfort zu gewährleisten. Zusätzlich werden Empfehlungen zur Realisierung von flexiblen Büroflächen präsentiert, um Designentscheidungen in der Konzeptphase oder bei der Renovierung zu unterstützen. Zusammenfassend zeigt diese Dissertation, dass die erwähnten flexiblen Parameter nicht unabhängig voneinander betrachtet werden können, um robuste Lösungen zu kreieren: Nur ein umfassendes Verständnis über deren Wechselwirkung kann Flexibilität in Bürogebäuden ermöglichen.

Contents

List of Figures

List of Tables

Nomenclature

Latin Symbols

Variable	*Description*	*Unit*
c	Specific heat capacity	J/(kg·K)
CV	Comfort violations	Kh/a
CV_{cold}	Comfort violations due to too cold conditions	Kh/a
CV_{hot}	Comfort violations due to overheating	Kh/a
E	Area specific yearly energy demand	kWh/(m²·a)
EUI	Energy use intensity	kWh/(m²·a)
$flex_i$	Flex index for each office space design configuration	-
h	Heat transfer coefficient for the human body	W/(m²·K)
$\dot{m}$	Mass flow rate	kg/(h·m²)
P	Area specific power	W/m²
p	Pressure	Pa
$P_{\mathrm{elec,fan}}$	Electrical fan power	W
P_{norm}	Specific norm power	W/m²
$\dot{Q}$	Heat transfer rate	W
R	Thermal resistance	m²·K/W
R_{x}	Thermal resistance in x-direction	m²·K/W
R_{z}	Thermal resistance in z-direction	m²·K/W
$SCOP$	Seasonal coefficient of performance	-
$SEER$	Seasonal energy efficiency ratio	-
SPF	Specific fan power	W/(m³·s⁻¹)
t	Time	h
T	Temperature	°C or K
T_c	Indoor comfort temperature	°C or K
T_{mr}	Mean radiant temperature	°C or K
T_{out}	Outside temperature index	°C or K
U	Heat transfer coefficient	W/(m²·K)

Greek Symbols

Variable	*Description*	*Unit*
Δ	Difference	-
η	Efficiency	-

ρ	Density	kg/m^3
σ	Standard deviation	-

Subscripts

Subscript	*Description*
24h	Mean value over a time period of 24 hours
adj	Adjacent airnode
air	Air
amb	Ambient
cc	Cooling coil
cond	Conduction
conv	Convective
cool	Cooling
core	Positioned in core area
cplg	Coupling air flow from a neighboring airnode
dif	Diffuse
dir	Direct
elec	Electricity for pumps and fans
ext	Extract (as extract air from room)
fan	Ventilation fan
hc	Heating coil
heat	Heating
hr	Heat recovery
inf	Infiltration
int	Internal (heat gains)
long	Longwave radiation
lower	Lower comfort limit
MR	Meeting room
office	Open-plan office
op	Operative
ref	Reference
set	Set point
sol	Solar radiation that is entering the airnode through a window
sols	Solar radiation that is absorbed by an internal shading device
sup	Supply
surf	Surface (as in the surface of a ceiling)
tot	Total
upper	Upper comfort limit
vent	Ventilation (as by an HVAC system)

Abbreviations

Abbreviations	*Description*
ACH	Air change per hour
AHU	Air handling unit
API	Application programming interface
BIM	Building information model
BPS	Building performance simulation
CAD	Computer-aided design
CP	Core/perimeter zoning
CV	Comfort violations
EUI	Energy use intensity
FG	Fine-grained zoning
HC	Heating and cooling curve(s)
HVAC	Heating, ventilation and air conditioning
IEQ	Indoor environmental quality
IHC	Ideal heating and cooling system (as defined in TRNSYS)
MV	Mechanical ventilation/HVAC system configuration no. 1
NS	North/south zoning
PID	Proportional–integral–derivative
RB	Room-based zoning
RC	Radiant ceilings/HVAC system configuration no. 2
RMSE	Root mean square error
TABS	Thermally-active building system/HVAC system configuration no. 3

1 Introduction

1.1 Flexibility in Office Buildings: A Challenge to Guarantee Thermal Comfort

As people spend most of their lifetime in buildings [1], maintaining comfortable indoor climate conditions that contribute to the occupants' satisfaction is of major importance. In most office buildings, the indoor climate conditions can be regulated using heating, ventilation and air conditioning (HVAC) systems. Typically, HVAC systems are responsible for 50 % of the building's energy consumption [2]. In total, buildings and construction is the largest energy-consuming sector, accounting for 36 % of the global final energy consumption and 39 % of global energy-related CO_2 emissions [3], including energy for the manufacturing of building materials. As the building stock is very long-lived, the International Energy Agency (IEA) reported that "action on appliances, equipment and systems is the key to achieving early low-cost CO_2 emissions reduction" [4].

To investigate the energy savings potential and assess the performance of HVAC systems before the operation phase, thermal building simulations can be carried out. However, previous research [5] identified that the actual energy demand of a building can be up to 2.5 times the predicted or simulated energy demand per year. This energy performance gap occurs especially in the first year of operation and after interior renovations. Therefore, the operation phase is considered to be a major contribution to the performance gap, with occupants and their behavior being identified as one of the main responsible factors. One possibility that building energy managers have to reduce the energy demand in the operation phase and to increase the occupant's thermal comfort, when confronted with a performance gap, is to adjust the HVAC system's control [5]. However, if the HVAC system's and office space design is not well-suited for the actual conditions in the building, such measures may only have a limited impact on the overall performance. Thus, to be able to make such adjustments while simultaneously maintaining an energy-efficient operation and high thermal comfort the HVAC system needs to be flexible. As also mentioned in [5]: "Therefore, future research on improving the flexibility of building system[s] is recommended". Even though there have been repeated research efforts to close the performance gap, the possibility of explicitly designing office spaces and HVAC systems to react flexibly and make effective adjustments during the operation phase has not been investigated in detail.

At the same time, furniture, space layout design and HVAC systems are subject to the most frequent changes during a building's operation phase [6]. Especially in office buildings, the space layout design needs to be repeatedly redesigned to meet tenants' requirements. Depending on the conditions of use, the space layout design in office buildings is changed every 3–7 years [6, 7]. Thus, in order to ensure a satisfactory performance, the HVAC systems must be adapted to these changes to maintain comfortable indoor climate conditions and guarantee that they are operated in an energy-efficient way. This can be challenging, because the HVAC system design is typically defined during the conceptual design phase when space layout design and office usage are not known exactly. Therefore, flexibility during the entire operation phase should be taken into account in the design process.

As a result, the main challenge is to achieve both flexibility and high thermal comfort in an energy-efficient way. To address these challenges, a robust solution for flexible space layout designs is required. In this context, a "robust" solution is defined as an HVAC system design, including its configuration and control zoning strategy, that can guarantee thermal comfort in an energy-efficient way, even when changing the space layout design. This dissertation aims at providing a "design for flexibility" approach for office spaces that can guarantee thermal comfort and energy-efficient operation during the entire operation phase. Specifically, it is investigated whether there are configurations of HVAC systems, control zoning strategies and space layout designs that can provide a robust solution to create comfortable indoor environments even in the face of significant future changes in the design parameters. Moreover, this work provides recommendations for an "office space design for flexibility" to make design decisions during the entire life cycle of an office building.

1.2 Hypothesis and Objectives

The following section describes the hypothesis and objectives of this dissertation.

Figure 1 shows the definitions of terms that are used to formulate them. To represent flexibility in office spaces, multiple variants of “design parameters” have to be investigated. The term “flexible design parameters” describes all variants of space layout design, HVAC system configuration and control zoning strategy that have been investigated in this work (marked in green). If one design parameter of each type is selected, a complete “office space design configuration” is made (marked in blue). Moreover, HVAC system configuration and control zoning strategy can be summarized with the term “HVAC system design”. Further definition of terms can be found in the Glossary.

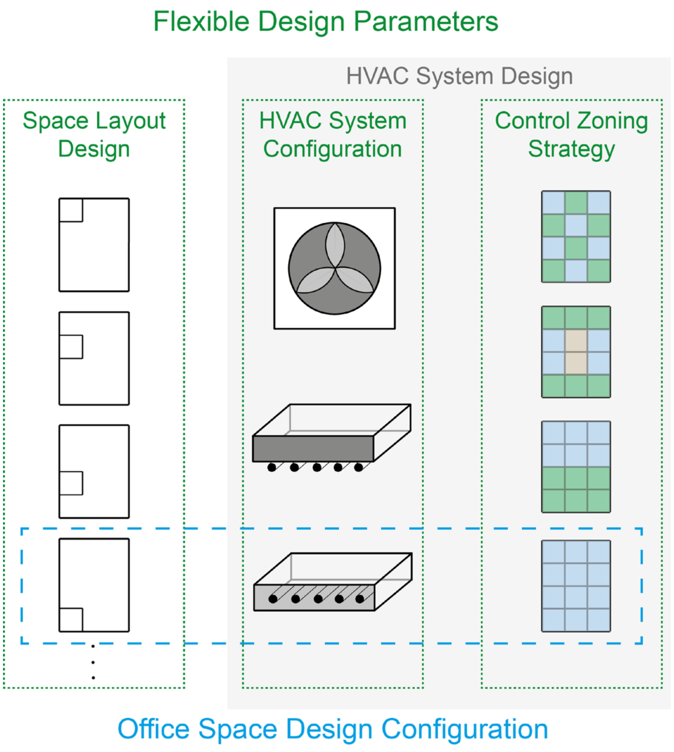


Figure 1. Definition of terms

Research Hypothesis

To design an office space for flexibility, three design parameters cannot be considered independently: space layout design (1), HVAC system configuration (2) and control zoning strategy (3). Certain configurations of these design parameters can guarantee thermal comfort and an energy-efficient operation, even in the event of variations within the office space design. The concept of an "office space design for flexibility" describes the procedure of selecting robust configurations of design parameters.

Objectives

The main objective of this dissertation is to enable a flexible office space design during the entire operation phase of an office building, without compromising on thermal comfort and energy efficiency. To achieve this, the following sub-objectives are defined:

Develop an approach to investigate flexible office spaces in terms of thermal comfort, energy demand and robustness	*Section 4.1*
Implement a simulation framework to model flexibility in office spaces, which includes the space layout design, HVAC system configuration and control zoning strategy.	*Section 4.1.2*
Identify suitable parameters to model a modern office building.	*Sections 4.2 – 4.3*
Identify the influence of each *flexible design parameter* (1–3) on thermal comfort and energy demand in office buildings:	*Sections 5.2 – 5.3*
(1) HVAC system configuration: Variation of systems with different thermal inertia	*Sections 5.2.1 – 5.2.4*
(2) Control zoning strategy: Variation of size, number and position of control zones and the definition of the controlled variable	*Sections 5.2.5 – 5.2.6*
(3) Space layout design: Variation of meeting room position in open-plan office	*Section 5.3*
Give recommendations for an "office space design for flexibility", which implies office space design *configurations* recommended for a flexible office space to guarantee high thermal comfort and an energy-efficient operation, robustly. In the recommendations, design scenarios for different life cycle phases of the office building are discussed.	*Section 5.4*

Design Scenarios and Research Questions

In the following, design scenarios that can be realized using the concept of *office space design for flexibility,* are described. For each design scenario, a research question is formulated that gives the requirements for the design parameters.

Table 1 shows which design parameters can be considered as variable parameters and which as fixed parameters in the specific design scenario.

Design Scenario No. 1

In the conceptual design phase, a new office space should be designed.

Which office space design configurations provide the highest thermal comfort, energy efficiency and flexibility?

Design Scenario No. 2

In the conceptual design phase, the HVAC system (configuration and control zoning strategy) should be designed without knowing the space layout design exactly.

Which HVAC system design (configuration and control zoning strategy) is the most robust to variations in the space layout design, regarding thermal comfort and energy efficiency?

Design Scenario No. 3

In the operation phase, a new space layout should be designed, because the tenants' requirements have changed. However, during this renovation, the HVAC system design (configuration and control zoning strategy) should not be adjusted.

Which space layout design provides the highest thermal comfort and energy efficiency for the given HVAC system design (configuration and control zoning strategy)?

Design Scenario No. 4

In the operation phase, the HVAC system design (configuration and control zoning strategy) needs to be retrofitted, but the space layout should not be adjusted.

Which HVAC system design (configuration and control zoning strategy) provides the highest thermal comfort and energy efficiency for the given space layout design?

Table 1. Fixed and variable design parameters for design scenario no. 1–4

Design scenario	**Life cycle phase**	**(1)** **Space layout design**	**(2)** **HVAC system configuration**	**(3)** **Control zoning strategy**
No. 1	Conceptual design	Variable	Variable	Variable
No. 2	Conceptual design	Variable	Fixed	Fixed
No. 3	Operation/renovation	Variable	Fixed	Fixed
No. 4	Operation/retrofitting (HVAC)	Fixed	Variable	Variable

1.3 Dissertation Structure

The structure of this dissertation is illustrated in Figure 2 and is described in the following section.

In the first chapter, the topic and the associated challenges, which are addressed in this work, are described. Resulting in the research hypothesis and the objectives of this dissertation. Moreover, exemplary design scenarios that can be realized using the concept of *office space design for flexibility* are described.

In the second chapter, the fundamentals to understand the developed approach are presented. In this section, the following topics are covered: office space design, including the building's life cycle, the office building typology, the office space layout design and typical HVAC systems; thermal comfort and its evaluation; and the building performance simulation, including the thermal zoning, the energy balance in an office space and a description of the thermal building simulation with TRNSYS.

In the third chapter, the state of the art, which is relevant for this work is highlighted. The focus of the literature research is on flexible office space design, which includes the space layout design, the HVAC system configuration and the control zoning strategy, and how to evaluate them in terms of flexibility, thermal comfort and energy efficiency. Moreover, the correlation between the topics is discussed and finally the gaps in the reviewed literature and the contribution of this dissertation is presented.

In the fourth chapter, the building model methodology, which uses parametric modeling and thermal building simulation, is presented and the developed approach to model flexibility in office spaces is described. Moreover, in a case study the approach is applied to a modern office building.

In the fifth chapter, the results from the case study are presented and discussed, focusing on the influence of the space layout design and HVAC system design on thermal comfort, energy demand and robustness. Moreover, recommendations for an *office space design for flexibility* are presented, which can be applied in other office spaces. To support these design decisions, a holistic view of the results are given, based on a new method called “flex index”.

In the sixth chapter, the main findings and contributions of this dissertation are summarized in the conclusion and an outlook with suggestions for future research and for future office spaces is given.

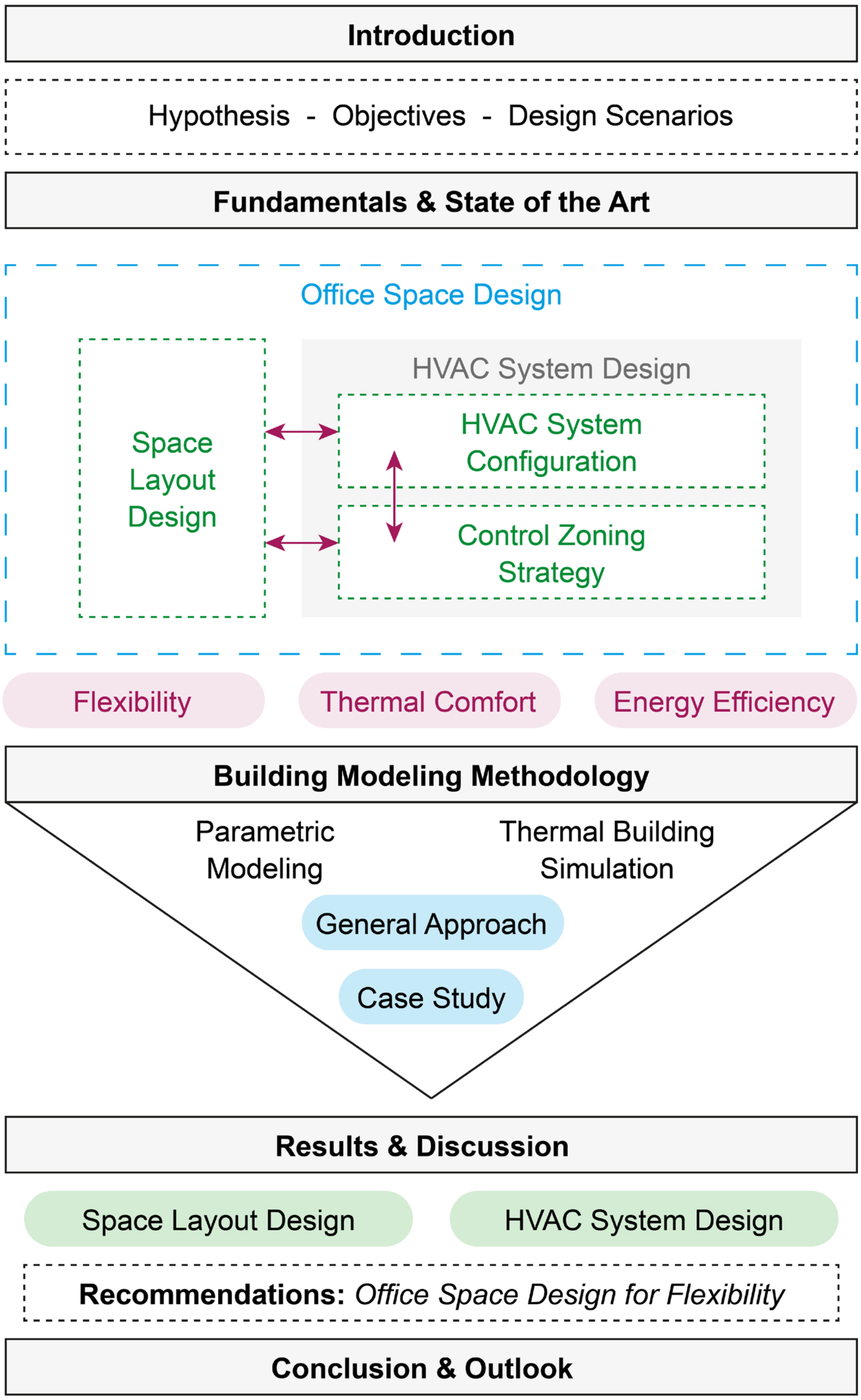


Figure 2. Structure of this dissertation

2 Fundamentals

In this chapter, the fundamentals to understand the concept and results that are described. Moreover, terms that are used in this dissertation are defined. This section contains general information about office space design, including the office building typology, the office space layout design and commonly used HVAC systems in office buildings. Furthermore, the principle of thermal comfort and approaches to evaluate the thermal comfort in buildings are briefly described. Finally, theoretical aspects of the building performance simulation are presented, including the thermal zoning, the energy balance and the thermal building simulation.

2.1 Office Space Design

The process of designing office spaces has fundamentally changed over the past few years. In former times, the design was oriented only with the aim of producing the most efficient use of space. Today, digitalization and thus the ability to work paperless and remotely has changed the requirements of office spaces. For most working activities, no permanent workspace is needed anymore. As mentioned in [8]: “In addition, the nature of work and processes is becoming more and more complex, networked, and specialized, which means that is becoming ever more important to be able to flexibly switch between team-oriented communication and a focused work environment”. Nevertheless, in office buildings the dependency between the building structure and the interior office space design are still of major importance to design workspaces that fit the occupants’ needs and can be used flexibly during the building’s life cycle. It is common practice to build office buildings in a grid-like construction to enable this flexibility in the space layout design [7, 8].

In this section, the fundamentals of office space design are explained.

2.1.1 The Building's Life Cycle

In order to understand how an office space design evolves, it is important to look at the entire life cycle of an office building. A building's life cycle has different phases, which can be found in Figure 3.

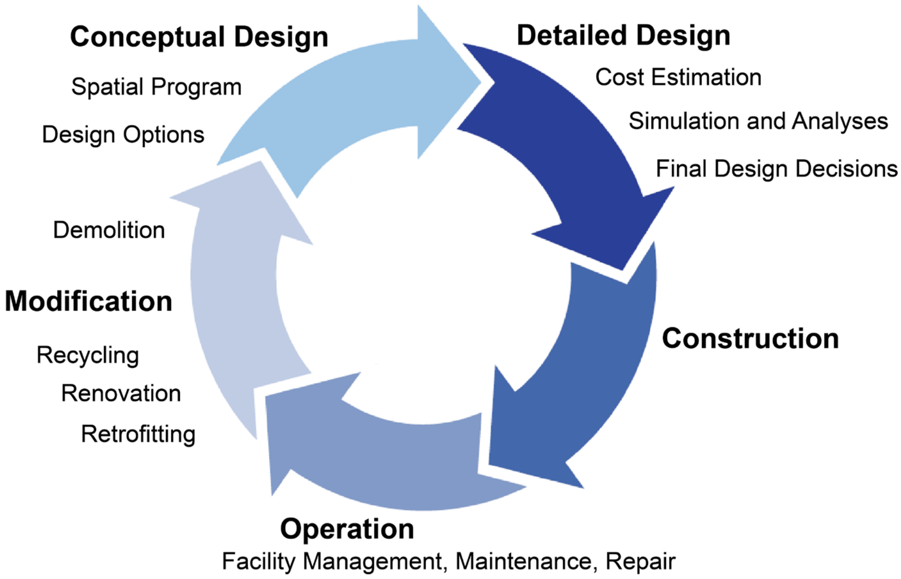


Figure 3. General life cycle of a building (based on [9])

The first step in a building's design process is the conceptual design phase, in which the architects develop the spatial program and design options are discussed. In this phase, also design decisions for the HVAC system are made. In the detailed design phase, simulation and analysis are carried out and the final building design, including the space layout design is developed. Then, the construction phase begins, during which the building is actually built on side. After finishing the construction works, the building is in the operation phase. During the operation phase, maintenance and adjustments of the building are necessary. If the tenants have new space requirements, modifications of space layout design (interior renovation) or the HVAC systems (retrofitting) have to be done. Moreover, if new tenants move into a building, the space layout design has to be adjusted. The modification phase is a temporary phase during the more general operation phase, during which the actual renovations are carried out. After approximately 40–120 years, the entire building needs to be demolished and the building's life cycle ends.

Depending on the conditions of use of office spaces, different occupancy periods occur, described in [10]: It is distinguished between new buildings, leased buildings and rented buildings. If a building is newly constructed only for the purpose of the tenant, the occupancy periods is typically 25 years or more. In contrast, a rented space with a tenant fit-out, as described in in next section, is occupied between 5–15 years, and a workplace that is rented including the equipment only up to 1 year. Thus, the durability of a space layout design may vary depending on the occupancy periods.

Based on the principle of dividing a building into different layers of change [11], Brand [6] developed a model with a building consisting of six layers, where each has a different lifetime and thus change at a different rate, illustrated in Figure 4. The first layer, called "site", describes the geographical context and the location of the building. This layer does not change during the building's lifetime. The second layer, called "structure", includes the load-bearing elements of the building. Their lifetime corresponds to the lifetime of the entire building and can range from 30–300 years, while most buildings are demolished after 60 years. The third layer, called "skin", represents the buildings envelope and needs to be replaced around every 20 years. The forth layer, called "service", includes the HVAC systems and infrastructure for communication, electricity and water. They need to be replaced every 7–15 years. Brand [6] emphasizes that many buildings are demolished, because the systems that need to be replaced are too deeply embedded in the buildings structure to exchange them easily. The fifth layer, called "space plan", represents the interior layout including walls, ceilings, floors and doors. The space layout design change around every 3 years. The sixth layer, called "stuff", includes furniture and objects of daily use, which are exchanged daily to monthly.

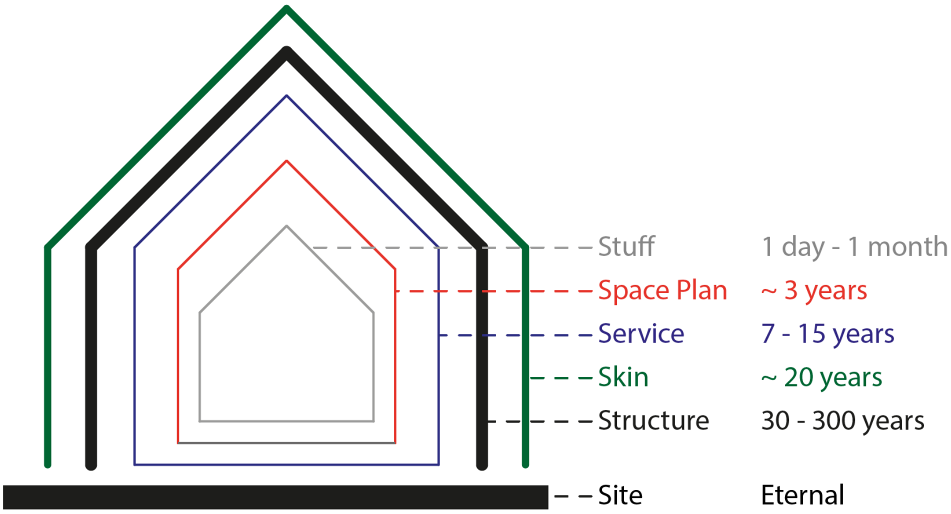


Figure 4. Model of the six layers of change (based on [6])

According to Neufert and Kister [7], also different lifetimes are assumed, depending on the part of the building. They assume that the load-bearing structure last around 50 years, the building envelope last around 20 years, the building technology including the HVAC systems needs to be retrofitted after 7–15 years, the space layout design needs to be renovated after 5–7 years, and the technical equipment and furniture have to be constantly renewed.

In total, it can be assumed that the space layout design needs to be adapted in order to meet the tenant's requirements in a period of around every 3–7 years. Moreover, the International Energy Agency stated that "as the building stock is very long-lived, action on appliances, equipment and systems is the key to achieving early low-cost CO_2 emissions reduction" [4]. Thus, renovations can be used to renew obsolete technologies and buildings parts.

2.1.2 Office Building Typology

The following section is based on Bielefeld [8] unless stated otherwise.

The outer building shape is mostly determined by the possibility of providing natural light in the building. Thus, the most common shape for office buildings are ribbon or slab buildings, which allows daylight to enter from the long building side, and linear office space arrangements. These building shapes usually have one or two central corridors, called double-loaded or triple-loaded. Figure 3 shows examples of the four common office building shapes with their functional areas where for example workplaces are located and vertical and horizontal circulation areas for corridors and staircases.

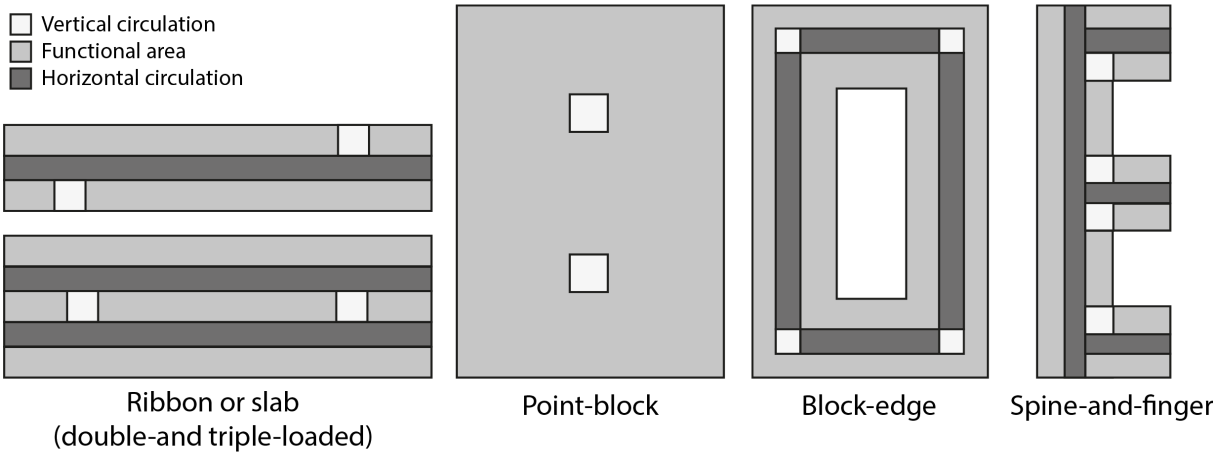


Figure 5. Examples of typical office building shapes, top view (based on [8])

The point-block building is used for open-plan offices. The advantage of this shape is the efficient space usage, because the corridor areas can be very small. Due to the large building depth, an increased building height is required to provide enough natural light in the building.

The other building shapes can be created using the ribbon building shape. One example for that process is the block-edge building (also called courtyard building). It consists of ribbon shapes that are enclosing an inner courtyard. This courtyard can be used for communication areas. Due to the shading from the building itself, the lighting on lower floors can be low. The spine-and-fingers building can also be created or extended from a ribbon building. It are similar to the block-edge building, but has an open courtyard.

In addition to the typical shapes, free-from shapes are also possible, which may be designed in response to a specific urban context. As this shape has no linear orthogonal structure, the free-form shapes are challenging for the space layout design and furnishing. The final building shape is sometimes an adaptation of the presented basic building shapes with modifications depending on the usage- and site-specific requirements.

Due to the typical rectangular shapes of office buildings, it is common practice to build with a structural system consisting of skeleton construction with grids of columns. The columns are arranged in the interior and along the facades. To better transfer the loads of the floor slabs to columns, the latter are usually moved away from the façade by 40–80 cm. To support the structure, loadbearing walls are used in core areas or sometimes in the building envelope.

During the planning process of an office building, different types of grids within the building are used to define the segmentation of the office space. These grid types are the planning grid, structural grid, façade grid and fit-out grid. In general, a grid is defined as follows [12]: “The grid is a virtual spatial/geometric coordinate system which fixes the position of points, lines, areas and volumes in space. A grid represents a uniform sequence of identical spacing: so-called ‘intervals’, which are based on a module dimension or its multiples.”

For the conceptual design phase of the building a planning grid is used, which only defines the approximate size of areas with different functions (e.g. office, circulation area, kitchen) and their position on the floor plan.

The structural grid is defined by the structural engineer and represents the position of the columns. The structure needs to fit the depth and subdivisions of the building, because the structural system determines the segmentation of the facade and thus the possible fit-out grid for the interior space layout design. Therefore, the structural grid should be considered in the conceptual design phase.

The façade grid is a subdivision of the structural grid and defines the position of the windows. The fit-out grid is also a subdivision of the structural grid and defines the geometric position of the interior drywalls. To be more precise, the axes of the fit-out grid “define the points where these dividing walls can be connected with the facade” [12]. Thus, the façade and fit-out grid are usually identical. In most office buildings, the process of defining the fit-out grid is made by the tenants to make the interior space suitable for their use during the operation phase. The fit-out grid may change during the operation phase, because the tenants change or have new space requirements.

The structural grid can be multiple times the fit-out grid or an offset of half a grid dimension depending on the design concept [12]. The grid's dimensions for office buildings are typically developed as multiples of the basic dimensions of 1.20 m, 1.25 m, 1.35 m or 1.50 m (see Table 2). As mentioned in [8]: "A basic building grid dimension of 1.35 m is often used for buildings above an underground parking garage, because the dimension of 5.40 m, which is four times the grid dimension, less the column thickness, results in a space that is sufficient for 2 parking spaces of 2.50 m [in] width." In the case study in this work, an office building with a basic grid of 1.8 m is investigated. In general, this gird construction provides high flexibility in creating a custom space layout design.

Table 2. Typical grid dimensions in office buildings [8]

Basic grid	1.5 x grid	2 x grid	3 x grid	4 x grid	5 x grid	6 x grid
1.20 m	1.80 m	2.40 m	3.60 m	4.80 m	6.00 m	7.20 m
1.25 m	1.875 m	2.50 m	3.75 m	5.00 m	6.25 m	7.50 m
1.35 m	2.025 m	2.70 m	4.05 m	5.40 m	6.75 m	8.10 m
1.50 m	2.25 m	3.00 m	4.50 m	6.00 m	7.50 m	9.00 m

The total length of the building is a multiple of the basic grid. The typical building depth depends on the office type and circulation. Depending on the number of employees in the office space, different office types can be chosen, as described the next section.

The building's floor height depends on the length, depth and office type, but also on the HVAC system installed. Some HVAC systems require suspended ceilings and thus the floor height needs to be increased. An overview of HVAC systems that are commonly used in office buildings are given in section 2.1.4.

2.1.3 Office Space Layout Design

Depending on the tenants' requirements, different office space layout designs can be created according to the grid dimensions. In the following section, the different office types, which enable different space layout designs, are explained. An overview of possible space layout designs is illustrated in Figure 4. In general, all types of office spaces consist of workstations, meeting rooms, circulation areas, a staff kitchen and service areas. The workstations are located in the cellular (cell), group, combi or open-plan offices. The rooms are separated by interior drywalls that can be installed along the fit-out grid, as described in section 2.1.2.

Moreover, the space layout design defines the location where different activities take place in the office space. It forms spaces for silent work and communication and thus influences the peoples' interaction and the way information flows in the building. For that reason, the choice of the space layout design should be part of the organizational strategy and suitable for the company and its daily work. In the following, the different office types, which define the possible space layout design variants, are described.

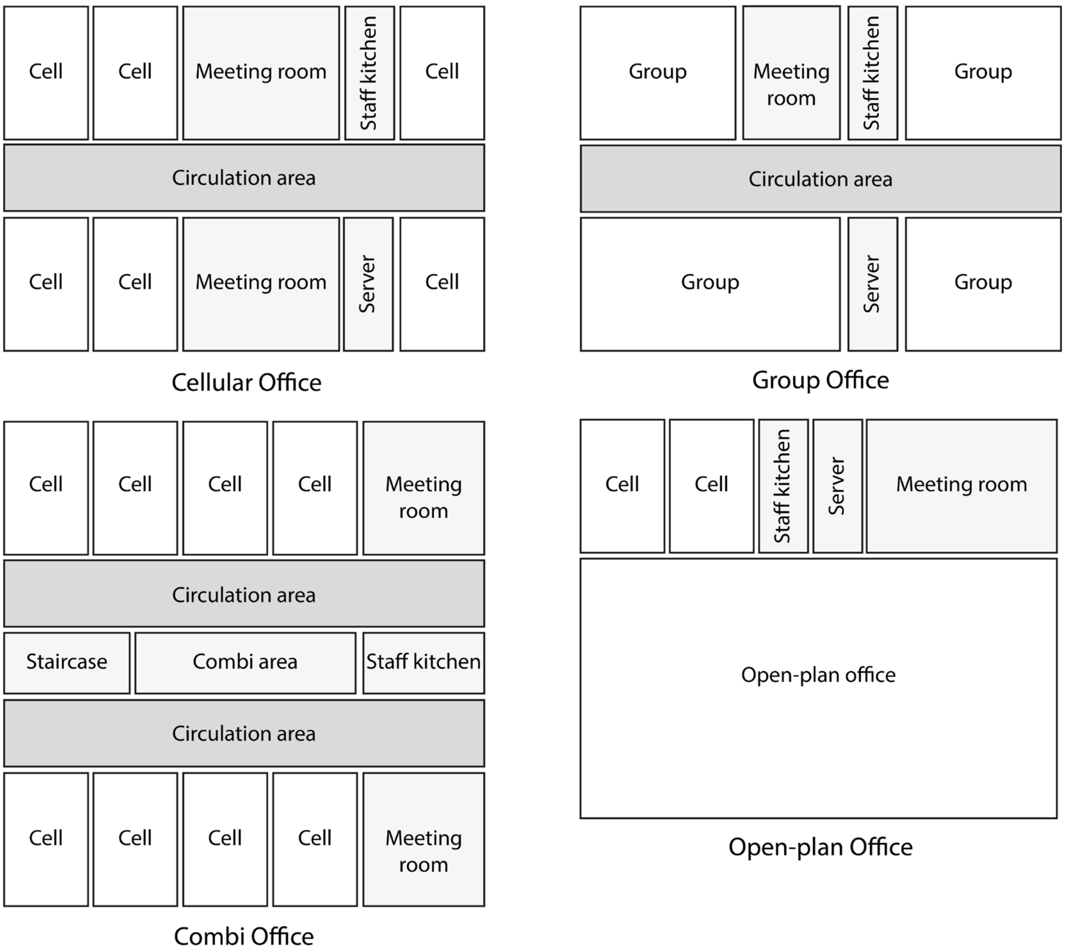


Figure 6. Space layout design with different office types (based on [8])

The cellular offices can be used as single or multi-person offices with up to six workstation. The rooms are arranged along the façade and are accessible through a shared corridor, which is the circulation area [13]. This office type is often used in combination with other types to provide room for concentrated working or activities that require a high degree of confidentiality [8].

The group offices can accommodate up to 25 workspaces. They are arranged along the circulation area and can be open to these or separated with interior drywalls [13]. This type of office enhances communication, thus separate rooms for concentrated work should be provided [8].

The combi offices combine cellular and open-plan offices. In this type, rooms are arranged around a common area that includes a so-called “combi area”, which is an area for communication and socializing. Glass walls and doors to the common area often separate the rooms. [13]

The open-plan office is a working landscape without corridors, which can has a size of 400 m^2 or more [13]. Within this open space, individual work and functional areas can be created by using furniture systems or small separating walls. This makes the space flexible to use depending on the tenants’ requirements. Therefore, open-plan offices are suitable for companies that have a dynamic organizational change. Due to the large number of workspaces, ensuring acoustic quality is a challenge, as well as room climate and lighting. [8]

In addition to the mentioned types, there is a new concept called “non-territorial work environments”, which is developed to create more individual and flexible working environments. This concept is based on the open-plan office type, but all above-mentioned types can be integrated. In this modern open-plan office, different zones for communication, individual work and other activities are provided. Thus, employees can flexibly choose the space that fits to their current task. Moreover, building elements can be flexibly arranged to create zones for communication or lounge areas and provide zoning in large spaces. [8]

2.1.4 HVAC Systems

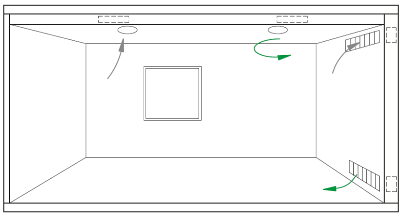
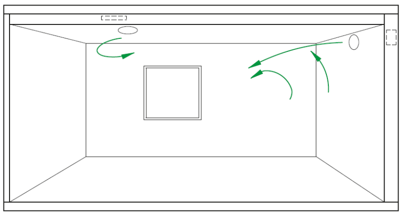
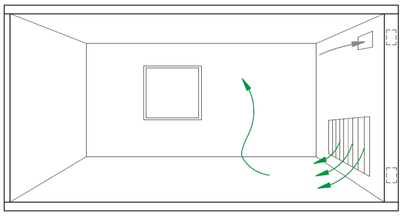
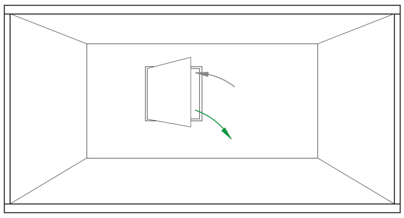
HVAC systems are installed in office buildings to provide the office space with fresh air, heating and cooling. The previous mentioned fit-out grid defines not only the dimensions of the ceiling elements and the position of the lighting, but also the position where HVAC system can be installed [12]. In general, HVAC systems consist of the system configuration itself and its control zoning strategy, which defines the space in the building that is conditioned by the system and can be controlled individually. More details on control zoning can be found in section 2.3.1. Depending on the local climate conditions, the building design and the usage of the interior space, heating or cooling of the interior space is required.

In the following section, common ventilation, heating and cooling systems for office buildings are presented. Regarding the flexibility of space layout design, HVAC systems that are integrated directly in the construction of the building, such as thermally-active building systems (TABS), provide more freedom of choice regarding the interior design. [14] This is the case, because no space for the construction elements of the systems need to be considered within the office space.

Ventilation Systems

In Table 3 common ventilation systems are presented, according to [14]. Ventilation systems are installed to provide fresh air in the building and can also be used to heat and cool the space. Alternatively, natural ventilation can be used by opening the window or other elements in the façade to provide fresh air. In this work, a supply and exhaust air system is investigated in different operation modes. This type of ventilation system supplies and exhausts air using a mechanical system. The supplied air can be conditioned and it is possible to integrate a heat recovery in the system. One disadvantage of this system is the high installation effort for the ducts. The advantage compared to natural ventilation is that the supply air temperature, the air change rate (ACH) and the air quality can be controlled more accurate.

Table 3. Ventilation systems in office buildings [14]

Ventilation systems	**Supply and exhaust air systems**	In general, supply and return air ducts are possible in the floor, ceiling and walls. Air ducts are integrated in the interior design.	
		Mixed ventilation Diffusors are located in the ceiling and upper wall area. Small air ducts lead to high air velocities in the room.	
		Displacement ventilation Large supply air inlets in the lower room area and exhaust air outlet on the top, lead to low air velocities in the room.	
	Natural ventilation	Opening windows or other elements in the façade to provide fresh air.	

Heating Systems

Even though the thermal insulation of buildings has been improved over the past years, buildings located in the moderate climate zone, such as Germany, still have a heating demand. Depending on the type of heating system, different temperature levels need to be provided by the system. If only a low supply temperature is required, which is the case for surface heating or TABS, energy from renewable source, such as geothermal collectors, can be integrated.

In this work, TABS, radiant ceilings and air heating using the previous mentioned supply and exhaust air system are investigated in detail. In Table 4 an overview of common heating systems for office spaces are presented, according to [14].

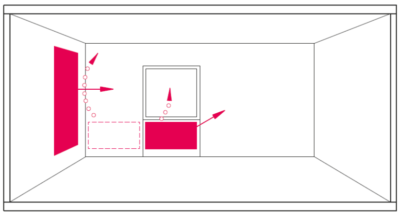
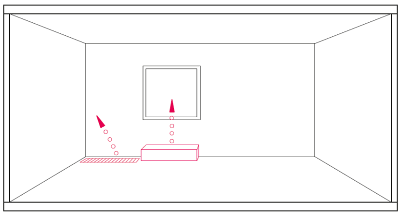
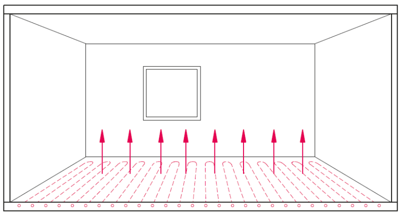
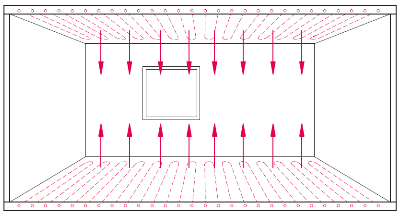
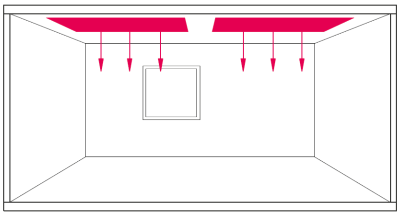
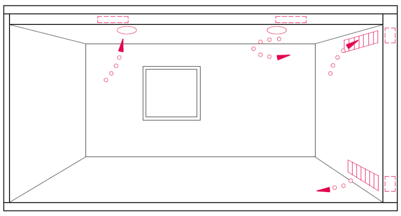
TABS are integrated in the concrete structure of the building and use the thermal capacity of the concrete to store the heat and transfer it to the room. TABS typically have large heat transfer surfaces, which is why only a low supply temperature is required. In office buildings, it is common practice to install TABS in the ceiling. For this, it must be considered that the ceiling area cannot be covered with acoustic elements or suspended ceilings. Moreover, TABS are slow reacting systems and thus cannot be controlled actively. However, through the high thermal inertia and the large surface area, they are able to maintain comfortable operative temperature in the room.

In contrast, radiant ceilings can be controlled precisely and transfer heat only in specific parts of space, if necessary. A high power supply is possible but also a high supply temperature is required. This means that low exergy systems, such as heat pumps, cannot typically be used in combination with radiant ceilings.

For air heating systems, the air can be heated in a centralized or decentralized way using heating coils. The system is fast reacting and can be actively controlled. One disadvantage is that high air change rates are typically necessary to cover the heating demand.

Typically, radiators or convectors are installed as additional or stand-alone heating systems under windows in office buildings, to avoid cold air falling down the window side. Using modern triple glazing, it is not implicitly necessary. Surface heating is a mixture of TABS and radiant ceilings. [14]

Table 4. Heating systems in office buildings [14]

Heating systems	**Radiators**	Radiators are often installed under windows and need to be integrated in the interior design.	
	Convectors	Convectors are often installed under windows or integrated in the floor.	
	Surface heating	Heating circuits are integrated in the screed.	
	TABS	Heating circuits are integrated in the concrete construction.	
	Radiant ceiling	Panels are suspended from the ceiling and provide local heating.	
	Air heating	Supply and return air ducts are possible in the floor, ceiling and walls. Air ducts are integrated in the interior design.	

Cooling Systems

Especially office buildings have a high cooling energy demand, because of the high internal gains caused by people, lighting and equipment. In addition, solar radiation and insufficient shading devices lead to undesired heating of the office space. In Table 5, common cooling systems are presented, according to [14].

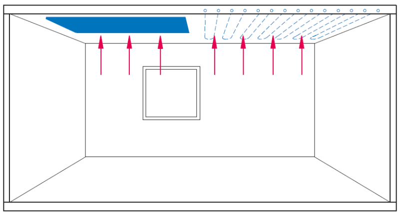
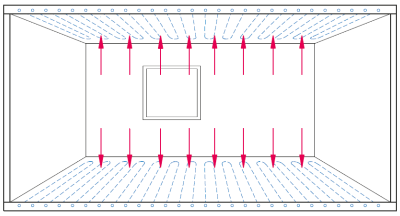
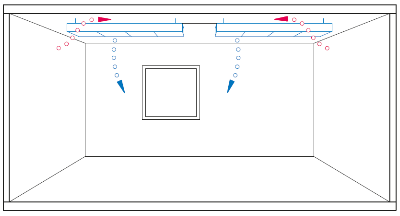
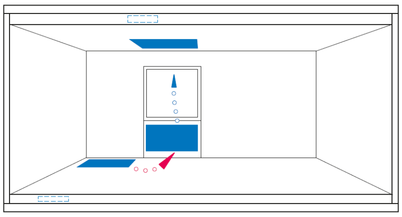
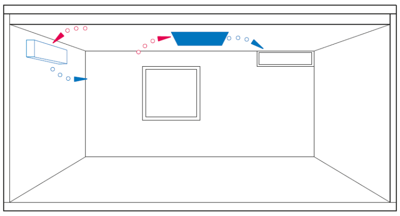
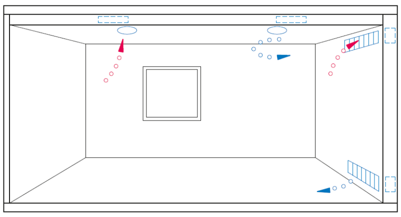
In this work, the following cooling systems are investigated: TABS, radiant ceiling and air conditioning/air cooling in combination with circulation air cooling. Induction units are often used as additional cooling units to serve high cooling demand that occur for example in meeting rooms.

The operating principle of TABS in cooling mode is similar to the operating principle in heating mode, described in the previous section on heating systems. For cooling purpose, TABS can only provide low cooling energy in comparison to other cooling systems, because only small temperature differences can be realized without condensation.

In contrast, radiant ceilings can provide high cooling energy. The design can vary from integrated pipes in the plaster to suspended ceiling panels or cooling sails. They can be compared with heating panels or surface heating in their functional principle. The controllability of radiant ceiling are high, but surface temperature below the dew point should be avoided.

Air conditioning or air cooling uses the same operating principles as air heating, described in the previous section on heating systems. Both are based on the supply and exhaust air ventilation system. An air conditioning system can also be using in circulation mode for circulation air cooling and to regulated the humidity of the air. [14]

Table 5. Cooling systems in office buildings [14]

Cooling systems	**Radiant ceiling**	Panels are suspended from the ceiling or cooling circuits are integrated in the plaster.	
	TABS	Cooling circuits are integrated in the concrete construction.	
	Chilled beams	Convectors are installed close to the ceiling and need to be integrated in the interior design.	
	Induction units	Induction units are often installed under windows and need to be integrated in the interior design.	
	Fan coils	Units are integrated in the upper room area or ceiling for local cooling.	
	Air conditioning/ air cooling	Supply and return air ducts can be placed in the floor, ceiling and walls and need to be integrated in the interior design.	

2.2 Thermal Comfort

Thermal comfort is an important factor of indoor environment quality and ensuring comfortable thermal conditions contributes the most to occupants' satisfaction [15]. The ASHRAE Standard 55-2010 [16] defines thermal comfort as "the condition of the mind in which satisfaction is expressed with the thermal environment". In the following sections, the influencing factors on thermal comfort and approaches to evaluate thermal comfort are presented. A more detailed description of the influencing factors and approaches can be found in the literature [17-19].

2.2.1 Heat Balance of the Human Body

The perception of thermal comfort derives from the need of the human body to maintain a constant internal temperature from around 36–38 °C. To evaluate the thermal state of the body, its heat balance has to be analyzed. [18]

In general, the heat balance between the human body and the environment depends on three personal factors: the metabolic heat production due to the activity level, the thermal resistance of clothing and the evaporative resistance of clothing. Moreover, four environmental variables are considered: the air temperature, the mean radiant temperature, the air speed and the relative humidity. A more detailed description of each influencing factor can be found in literature [21, 22].

Depending on the result of the heat balance, the thermoregulatory system of the human body reacts in a way that it balance out the fluctuations and maintains the energy balance equal to zero. [18] These principles are the basis for Fanger's comfort model, described in the next section.

2.2.2 Operative Temperature

When evaluating the thermal comfort, approaches often refer to the operative temperature to define the requirements for the indoor environment. As described in [17], the operative temperature is defined as the uniform temperature of an imaginary enclosure in which the exchange of dry heat by radiation and convection will be the same as in the actual environment.

It can be expressed as [23]:

$$T_{\mathrm{op}} = \frac{(h_{\mathrm{conv}} \cdot T_{\mathrm{air}} + h_{\mathrm{rad}} \cdot T_{\mathrm{mr}})}{(h_{\mathrm{conv}} + h_{\mathrm{rad}})} \tag{2-1}$$

where

T_{op} is the operative temperature,

T_{air} is the air temperature,

T_{mr} is the mean radiant temperature of the surrounding surfaces,

h_{conv} is the convective heat exchange coefficient and

h_{rad} is the radiant heat exchange coefficient for the human body.

Under certain conditions, that are most of the time present in air-conditioned spaces, the operative temperature can be simplified as followed [17]:

$$T_{\mathrm{op}} = \frac{(T_{\mathrm{air}} + T_{\mathrm{mr}})}{2} \tag{2-2}$$

Equation (2-2) can be applied if the occupant's metabolic rate is between 1.0 met and 1.3 met, no air velocities greater than 0.2 m/s occur and the difference between the air temperature and the mean radiant temperature is below 4 °C.

2.2.3 Static and Adaptive Approach

In this section, the static and adaptive approaches to evaluate the occupant's satisfaction with the interior thermal conditions are presented.

On the one hand, one static or heat balance approach, which relates to the heat balance of a human body (described in section 2.2.1), is used in the standard EN ISO 7730:2005 [24]. In order to maintain a constant human body temperature the human body interacts with the surrounding environment [25]. The basis for Fanger's comfort model [25] are steady-state experiments in controlled climate chambers. The static approach derives from this model combined with an empirical study that predicts the occupant thermal comfort.

On the other hand, the adaptive approach, which defines a comfortable temperature range depending on the prevailing outdoor climate conditions, is described in in the standards EN 15251:2012 [26] and ASHRAE 55:2010 [16]. An adaptive approach uses data from field studies of occupants in buildings and refers to a higher range of comfortable conditions, because it is assumed that the occupant can adapt to the prevailing climate conditions. As described by de Dear and Brager [27], three categories of thermal adaptation can be distinguished: the behavioral, physiological and psychological adaptation. As a result, the comfort temperature depends on the environment the occupant is exposed to. Moreover, it is assumed that the preferred indoor temperature of the occupant varies with the outdoor climate conditions. Therefore, those models are based on the occupants' behavior and the outdoor climate conditions. Derived from field studies with extensive databases [27, 28], adaptive comfort models and standards have been defined. De Dear and Brager [27] define an adaptive model as: "a linear regression model that relates indoor design temperature or acceptable temperature ranges to outdoor meteorological or climatological parameters". In general, to calculate the optimum comfort temperature the following form of Equation (2-3) can be used [28]:

$$T_c = a \cdot T_{out} + b \qquad (2\text{-}3)$$

where

T_c is the indoor comfort temperature,

T_{out} is the outside temperature index and

a, b are constants.

A detailed description of both the static and adaptive approaches can be found in [18]. In this dissertation, an adaptive approach is used to evaluate thermal comfort in flexible office spaces. This adaptive approach is defined in the national appendix of DIN EN 15251 [26]. As stated in Equation (2-4)–(2-6) the comfortable operative room temperature (T_{op}) is defined, depending on the ambient temperature (T_{amb}). Moreover, a dead band of $\pm$2 K around the temperature set point curve is applied.

$$T_{\mathrm{op}} = 22 \qquad (T_{\mathrm{amb}} \leq 16\ °\mathrm{C}) \qquad (2\text{-}4)$$

$$T_{\mathrm{op}} = 18 + 0.25 \cdot T_{\mathrm{amb}} \qquad (16\ °\mathrm{C} < T_{\mathrm{amb}} < 32\ °\mathrm{C}) \qquad (2\text{-}5)$$

$$T_{\mathrm{op}} = 26 \qquad (T_{\mathrm{amb}} \geq 32\ °\mathrm{C}) \qquad (2\text{-}6)$$

2.3 Building Performance Simulation

In order to predict the performance of a building during its life cycle, building performance simulation (BPS) can be carried out. BPS uses building models, which are for example based on physical fundamental principles, to formulated a building in mathematical descriptions [29]. One part of the BPS is the thermal building simulation, which is used to model the thermal behavior of a building. This model-based analysis can be used in the conceptual and detailed design phase for evaluating the building design [29], the HVAC system configuration [30] and in the operation phase for example for an model-based control of buildings [31].

To perform a thermal building simulation the building needs to be divided into thermal zones. Based on the energy balance in a thermal zone, the energy demand and thermal behavior of the zone is predicted. As input parameters, the thermal building simulation needs the building's geometry, the construction material's properties, the weather data of the location, the internal heat gains by people, equipment and lighting, the specifications for the HVAC system, as well as schedules for the operation and control of the systems. All these parameters are in dynamic interaction and influence each other. [30]

In the following, first the thermal zoning to prepare a building for a thermal building simulation and the control zoning to define the area that is conditioned by an HVAC system are described. Then, the energy balance in an office space is illustrated. Afterwards, the mathematical models for the thermal building simulation with TRNSYS are explained.

2.3.1 Thermal Zoning

Most thermal building models rely on thermal zones to separate the space within the building into smaller areas and then calculate the respective energy demand and thermal behavior of these areas. Thus, "each zone forms a control volume over which heat transfer into and out of the zone is analyzed" [32]. A description of the energy balance and the heat transfer for an office space can be found in the next section.

In literature, several terms can be found: thermal zone [33], thermal block [34] and HVAC zone [34]. Nevertheless, all terms indicate the same principle of dividing a building into areas with the same thermal behavior. Within a thermal zone, the properties of the space are assumed to be homogeneous [33].

The method of thermal zoning is used in thermal building simulations. This principle, as described in Shin and Haberl [35], is not well documented and no standardized method of thermal zoning that can be applied easily to all types of buildings exists. The ASRHAE

Standard 90.1-2016 [33] gives some general guidelines that do not clearly indicate the size and position of thermal zones in a building. The guidelines recommend to separate core and perimeter areas in different thermal zones, separated by the façade's orientation. Moreover, each floor should be in a separate thermal zone.

In literature [34], the term "HVAC zones" refers to a space in a building, which indoor climate is conditioned by the same HVAC system. The HVAC zones of a building are defined in HVAC plans. In the modeling guideline of the Commercial Energy Service Network (COMNET) [34], which is an addition to the ASHRAE Standard 90.1-2016 [33], an HVAC zone is describes as "a physical space within the building that has its own thermostat and zonal HAVC system for maintaining thermal comfort". Moreover, in this context a so-called "thermal block" can contain more than one HVAC zone and thus summarize HVAC zones with similar thermal requirements and a single control device. In summary, a single sensor measures the thermal behavior of an HVAC zone or a thermal block. Thus, the space in an HVAC zone has the same set point for the indoor environmental conditions, such as air temperature, CO_2 or relative humidity.

In this work, the term "control zone" is used for HVAC zones as they refer to the possibility of controlling the defined space within the zone. The term "thermal zone" describes a thermal zone in a thermal building simulation model.

2.3.2 Energy Balance

To understand the mathematical model behind the thermal building simulation, the heat transfer mechanism that influences the energy balance of a thermal zone need to be considered [29]. They can be categorized by the way heat is exchanged between the thermal zone and its surroundings, consisting of convection, conduction and radiation.

In thermodynamics, energy that crosses the boundaries of a system is called heat if the energy transport is caused by a temperature difference between the system and its surroundings. [36] In general, the energy balance is calculated for each thermal zone and is used to obtain the heating and cooling energy demand of the building.

According to DIN 18599 [37], the energy that is required in the thermal zone depends on the heat sinks and sources that influences the thermal zone. Depending on whether the energy is transferred into or out of the thermal zone, a heat sink or respectively a heat source is considered. These heat sinks and sources are categorized in four groups, illustrated in Figure 5. The first group consists of conduction heat sinks or sources (Q_{cond}) considering conduction through construction elements ($Q_{cond,con}$) and thermal bridges ($Q_{cond,tb}$), marked in green. The second group consists of ventilation heat sinks or sources (Q_{vent}) considering infiltration ($Q_{vent,inf}$), mechanical ventilation ($Q_{vent,mech}$) and natural ventilation when opening the windows ($Q_{vent,nat}$), marked in blue. The third group consists of heat sources through solar radiation (Q_{sol}) considering solar radiation through opaque ($Q_{sol,op}$) and transparent ($Q_{sol,trans}$) building elements, marked in orange. The fourth group consists of internal heat sinks or sources (Q_{int}) considering internal heat sources from people ($Q_{int,p}$), equipment ($Q_{int,eq}$), lighting ($Q_{int,li}$) and internal heat sinks or sources from the HVAC system ($Q_{int,HVAC}$), marked in red. [37]

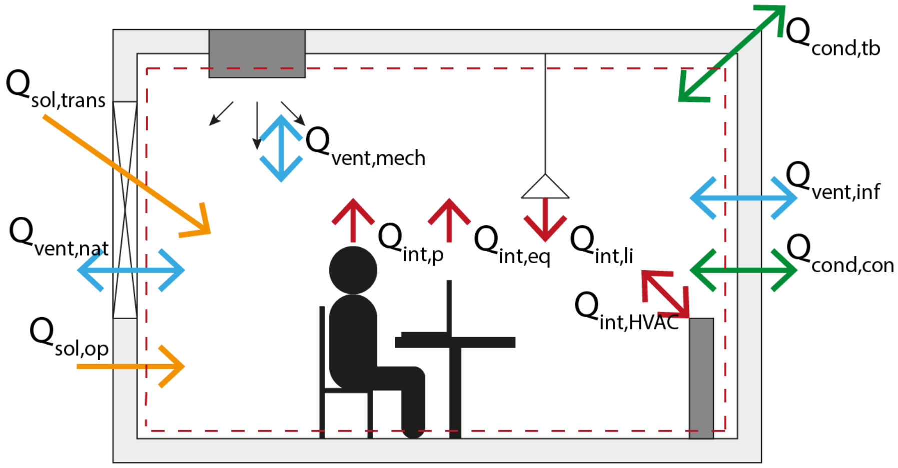


Figure 7. Heat sinks and sources in a thermal zone for an office space

2.3.3 Thermal Building Simulation with TRNSYS

One common tool to perform a thermal building simulation is TRNSYS [38]. With TRNSYS, building systems and buildings with multiple thermal zones can be simulated. To set up a simulation model with TRNSYS, the components from a library, the so-called TYPEs, can be used. Each TYPE describes a system mathematically. Using the multizone building model (TYPE 56) the thermal behavior of a building can be simulated. The thermal building model used by TRNSYS is based on an energy balance of a thermal zone. In TRNSYS, each thermal zone consists of one or more *airnodes*. These airnodes are used to calculate the energy balance of its control volume, which is marked in red in Figure 8.

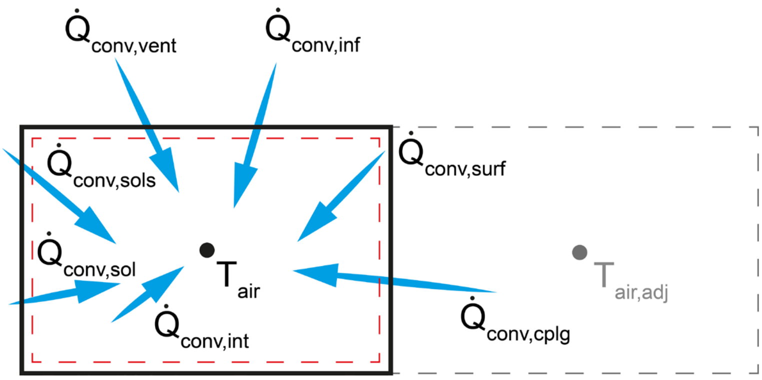


Figure 8. Convective heat transfer for an airnode in TRNSYS (based on [39])

To calculate the convective heat transfer to an airnode, seven variables are considered in the TRNSYS multizone building model, illustrated in Figure 8. The convective heat transfer to the airnode ($\dot{Q}_{\mathrm{conv}}$) is then calculated as follows [39]:

$$\dot{Q}_{\mathrm{conv}} = \dot{Q}_{\mathrm{conv,surf}} + \dot{Q}_{\mathrm{conv,inf}} + \dot{Q}_{\mathrm{conv,vent}} + \dot{Q}_{\mathrm{conv,int}} + \dot{Q}_{\mathrm{conv,cplg}} + \dot{Q}_{\mathrm{conv,sol}} + \dot{Q}_{\mathrm{conv,sols}} \quad (2\text{-}7)$$

where

$\dot{Q}_{\mathrm{conv,surf}}$ is the convective gains from surfaces,

$\dot{Q}_{\mathrm{conv,inf}}$ is the infiltration gains by the infiltration of the outside air,

$\dot{Q}_{\mathrm{conv,vent}}$ is the ventilation gains by an HVAC system,

$\dot{Q}_{\mathrm{conv,int}}$ is the convective gains caused by internal heat sources, such as people, equipment, lighting, radiators, etc.,

$\dot{Q}_{\mathrm{conv,cplg}}$ is the gains due to an air flow from a neighboring airnode,

$\dot{Q}_{\mathrm{conv,sol}}$ is the convective gain by the solar radiation that is entering the airnode through a window and

$\dot{Q}_{\mathrm{conv,sols}}$ is the convective gain by the solar radiation that is absorbed by an internal shading device.

When defining multiple airnodes within one thermal zone in TRNSYS, a coupling statement allows defining the air flow between them. The convective heat gain resulting from this coupling is described with $\dot{Q}_{\mathrm{conv,cplg}}$. The thermal capacity of an airnode is a separate input in addition to the volume of the thermal zone, because it also contains the thermal capacity of all objects within that volume, such as furniture.

The longwave radiation can be calculated in a simplified manner using the star network model or in a more detailed way using the Gebhart matrix [40, 41]. When multiple airnodes are defined for one thermal zone, it is recommended to use the detailed radiation model. Therefore, in this work the detailed radiation model is used. The Gebhart method uses view factors to calculate the Gebhart matrix for longwave radiation. Thus, the longwave radiative heat transfer ($\dot{Q}_{\mathrm{rad,long}}$) only depends on the temperature vector, optical and geometrical properties, as well as on the Stefan-Boltzmann constant. Hence, the energy balance for detailed radiative heat transfer to the airnode ($\dot{Q}_{\mathrm{rad}}$) is defined as follows [39]:

$$\dot{Q}_{\mathrm{rad}} = -(\dot{Q}_{\mathrm{rad,sol,dir}} + \dot{Q}_{\mathrm{rad,sol,dif}} + \dot{Q}_{\mathrm{rad,long}} + \dot{Q}_{\mathrm{rad,int}}) + \dot{Q}_{\mathrm{rad,surf}} \qquad (2\text{-}8)$$

where

$\dot{Q}_{\mathrm{rad,sol,dir}}$ is the radiative gains by direct solar radiation,

$\dot{Q}_{\mathrm{rad,sol,dif}}$ is the radiative gains by diffuse solar radiation,

$\dot{Q}_{\mathrm{rad,long}}$ is the radiative gains by longwave radiation,

$\dot{Q}_{\mathrm{rad,int}}$ is the radiative gains by point sources (internal gains) and

$\dot{Q}_{\mathrm{rad,surf}}$ is the radiative gains by from inside wall or window surfaces.

For direct and diffuse solar radiation, it is distinguished between primary and secondary distribution, which refers to non-reflected and single-reflected solar radiation. Moreover, diffuse solar radiation can also be multiply reflected. [39]

One part of the solar radiation that is entering the airnode through an external window is directly transferred as a convective gain ($\dot{Q}_{\mathrm{conv,sol}}$) to the air. The calculation of the distribution of the remaining direct and diffuse solar radiation is based on the geometry of the thermal zone, which the solar radiation is entering independent from the number of airnodes within in the thermal zone. In the detailed radiation model, the distribution of the direct solar shortwave radiation is calculated according to the current sun position for each time step. Doing so, the geometrical representation of the multizone building model is used. The diffuse shortwave solar radiation is calculated similar to the longwave radiative heat transfer ($\dot{Q}_{\mathrm{rad,long}}$) using the Gebhart matrix [40, 41]. [39]

To calculate the energy demand for a multizone building, it is possible to use the mathematical description of HVAC systems integrated in the multizone building TYPE 56 or to use separate TYPEs that define the systems in more detailed. In the following, the mathematical descriptions of the components for the HVAC systems used in this work are shortly presented. A detailed description of each TYPE can be found in the TRNSYS documentation [39].

Ideal Heating and Cooling System

The ideal heating and cooling system (IHC) is a component, which is integrated in TYPE 56, can be used to calculate the energy required to control the temperature in the airnode in an idealized way. “Therefore the heating and cooling energy flow is directly connected to the airnode air temperature node” [39].

This method is described in [39] as follows: If the airnode temperature is within the defined temperature range, no power is supplied to the airnode by the system. If the airnode temperature is below or above that temperature range at the end of a time step, power is supplied to the airnode throughout the time step until it just reaches the temperature set point again. When the component is in heating or cooling mode, the temperature change of the air in the airnode is linear.

Mechanical Ventilation

For simulating the performance of a mechanical ventilation, TYPE 336 can be used, which is specified as air handling unit (AHU) with sensible and latent heat recovery. As described in [42], with TYPE 336 the energy demand for heating or cooling the air to meet a defined set point can be calculated. The AHU can consider air heat recovery, humidification, dehumidification and a bypass mode. The latter allows the system to recirculate the extracted air from inside the airnode back into the airnode directly, as illustrated in Figure 9.

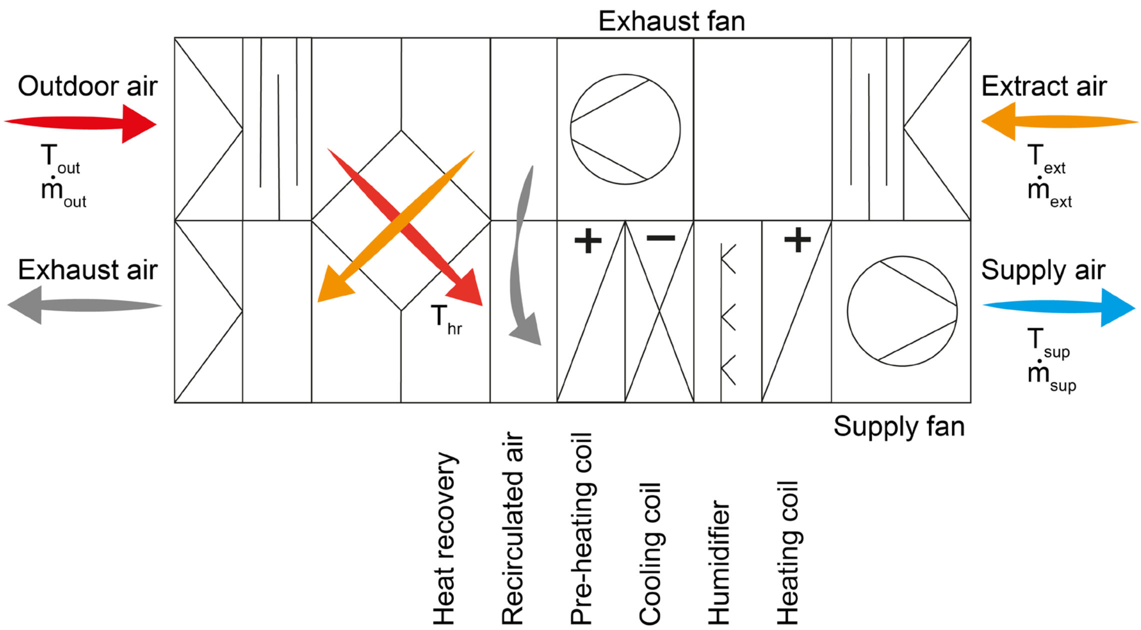


Figure 9. AHU schematic in cooling mode (based on [42])

When entering the AHU, the outside air passes the heat recovery unit first. Depending on the temperature of the extracted air from the airnode (T_{ext}), heat can be transferred to the outside air. The efficiency of the sensible heat recovery depends on the mass flow rate of the outside air ($\dot{m}_{\mathrm{out}}$), the mass flow rate of the extracted air ($\dot{m}_{\mathrm{ext}}$), the temperature of the outside air (T_{out}) and the temperature of the extracted air (T_{ext}).

The AHU operates in heating mode if the outside air temperature after heat recovery (T_{hr}) is below the supply air set point temperature ($T_{\mathrm{sup,set}}$). The required heating power by the pre-heating coil ($\dot{Q}_{\mathrm{heat,hc}}$) is calculated as follows [42]:

$$\dot{Q}_{\mathrm{heat,hc}} = \dot{m}_{\mathrm{out}} \cdot c_{\mathrm{air}} \cdot (T_{\mathrm{sup,set}} - T_{\mathrm{hr}}) \tag{2-9}$$

where c_{air} is the specific heat capacity of the air.

The AHU operates in cooling mode if the outside air temperature after heat recovery (T_{hr}) is above the supply air set point temperature ($T_{\mathrm{sup,set}}$). The required cooling power by the cooling coil ($\dot{Q}_{\mathrm{cool,cc}}$) is calculated as follows [42]:

$$\dot{Q}_{\mathrm{cool,cc}} = \dot{m}_{\mathrm{out}} \cdot c_{\mathrm{air}} \cdot (T_{\mathrm{sup,set}} - T_{\mathrm{hr}}) \tag{2-10}$$

The electric fan power for the supply and exhaust fans ($P_{\mathrm{elec,fan,sup}}, P_{\mathrm{elec,fan,ext}}$) is calculated based on the actual supply and return air flowrates ($\dot{m}_{\mathrm{sup}}, \dot{m}_{\mathrm{ext}}$), pressure drops ($\Delta p_{\mathrm{sup}}, \Delta p_{\mathrm{ext}}$) and fan efficiency ($\eta_{\mathrm{fan}}$) as follows:

$$P_{\text{elec,fan,sup}} = \left(\frac{\Delta p_{\text{sup}} \cdot \dot{m}_{\text{sup}}}{\rho_{\text{air}} \cdot \eta_{\text{fan}}}\right) / 1000 \quad (2\text{-}11)$$

$$P_{\text{elec,fan,ext}} = \left(\frac{\Delta p_{\text{ext}} \cdot \dot{m}_{\text{ext}}}{\rho_{\text{air}} \cdot \eta_{\text{fan}}}\right) / 1000 \quad (2\text{-}12)$$

where ρ_{air} is the density of the air.

When using the bypass mode, the amount of air that is recirculated from the extracted air can be defined. In normal operation mode when the AHU operates only with outside air, the recirculation fraction is zero. If no outside air is required, recirculation fraction can be set to one.

More details about the AHU model can be found in [42].

Radiant Ceiling

The input parameters for the radiant ceiling model, integrated in TYPE 56, are defined according to DIN EN 14240 [43]. The total power needed by the radiant ceiling depends on the thermal resistance of the ceiling, the fluid inlet temperature, the mean fluid temperature, the mean temperature of the radiant ceiling and the operative temperature in the airnode. To calculate the heat transfer coefficient (U_{RC}) the specific norm power (P_{norm}) can be used for the following approximation [39]:

$$U_{\text{RC}} = 0.6 \cdot \exp\left(\frac{0.0469 \cdot P_{\text{norm}}}{3.6}\right) \cdot 3.6 \quad (2\text{-}13)$$

More details about the radiant ceiling model can be found in [39].

The mass flow in the pipes and the supply temperature of the RC is controlled with the differential controller (TYPE 2 [44]).

Thermally-Active Building System

To model a thermally-active building system (TABS), a component integrated in TYPE 56 can be used. Usually, the finite difference method or finite element method are used to calculate the three-dimensional heat transfer a building element. As this requires complex calculations and long calculation time, the TYPE 56 uses a simplified method, described in detail in [39]. This method is based on a resistance network of the TABS.

The total resistance (R_{tot}) of the system can be calculated as follows [39]:

$$R_{\text{tot}} = R_{\text{x}} + R_{\text{z}} + R_{\text{conv}} + R_{\text{cond}} \tag{2-14}$$

where R_{x} is the resistance in x-direction, which only depends on the distance between the pipes, the pipe diameter and the thermal conductivity of the material. R_{z} is the resistance in z-direction, which describes the temperature change of the fluid along the pipe coil. The thermal resistances ($R_{\text{conv}}, R_{\text{cond}}$) describe the heat transfer from the fluid through the pipe shell to the concrete. It is distinguished between the thermal resistance by convection (R_{conv}) and the thermal resistance by conduction (R_{cond}). All resistances are calculated according to [45].

More details about the TABS model can be found in [39].

2.3.4 Simulation Framework

In this work, the open source tool TRNLizard [46] is used to setup the thermal building model for the simulation with TRNSYS. TRNLizard is an application programming interface (API) plugin for the generative tool Grasshopper [47] for Rhinoceros 6 [48]. Grasshopper is available as an API plugin for Rhinoceros 6, which is a computer-aided design (CAD) program. It can be used to setup a parametric building model using visual programming language. The complete workflow with TRNLizard is illustrated in Figure 10.

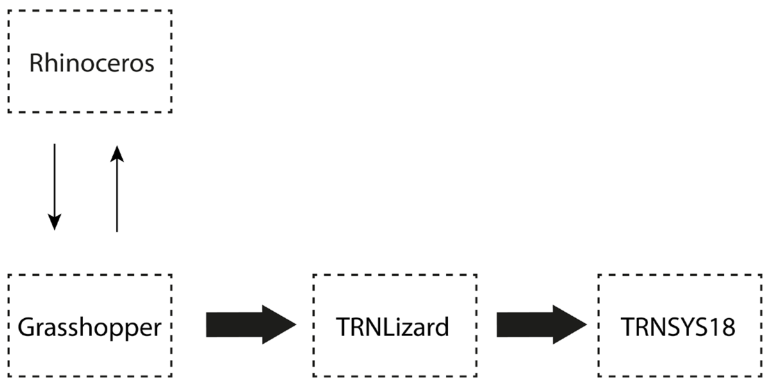


Figure 10. Workflow with TRNLizard

A parametric building model is a digital representation of a building and based on objects that are defined with parameters and rules, as described in [49]. Using these dependencies, the generation of a high number of variants within a short time can be enabled. Parametric modeling is often used in architectural design, because different designs can be generated and evaluated efficiently. Moreover, parametric models can be used for thermal building simulations to generate different building models fast, thus facilitating the optimization of their parameters. In practice, generative tools, such as Grasshopper, which work with visual programming languages, are used to generate parametric models. Those tools use blocks containing a program code that are connected with other blocks to build up a logical system.

TRNLizard can be used to connect a parametric building model with the thermal building simulation software TRNSYS. TRNLizard allows completely automated setup of the thermal building model and the generation of all TRNSYS input files. Geometric elements and their associated properties modelled in Rhinoceros and Grasshopper can be used in the TRNLizard component to define the building model. All parameters that are necessary for the thermal building simulation can be defined with TRNLizard. Moreover, the parametric functionalities from Grasshopper can be used. By defining the changing parameters, different variations of geometry and other modelled aspects be can be investigated. Accordingly, the simulation models of the different variants are generated with TRNLizard. In this workflow, TRNSYS is used as component library and simulation engine. [46]

3 State of the Art

In this chapter, the literature on thermal comfort in flexible office spaces is reviewed, focusing on the flexible office space design, robust HVAC system design and control and developments in thermal zoning for the building performance simulation (BPS). Each section includes a summary of the most important points for this dissertation obtained from the reviewed literature. Moreover, the contribution of this dissertation is described, which correlates the above mentioned topics in a novel way to enable an *office space design for flexibility* approach.

3.1 Flexible Office Space Design

While the building's envelope and its structural elements are in long-term use, the interior space experiences numerous shorter-term changes to adopt to the prevailing needs of the occupants. [50, 51] Especially in office buildings, the space layout needs to be repeatedly redesigned to meet the tenants' requirements in the operation phase. As mentioned in [8]: "For this reason, the design of office buildings is much more than a schematic arrangement of layouts; rather, it presents a highly tailored task involving building as well as interior design, with the fundamentals having to be established anew for each project".

This is also reflected in the life cycle cost of a building: "Many buildings demonstrate that initial construction costs are a small fraction of the lifetime construction costs of the building" [51]. Moreover, in office buildings, only a quarter of the total life cycle embodied energy is required in the initial construction of the building [52]. The remaining embodied energy accounts for renovation, replacement, maintenance and rearrangement of building systems and interior structures.

Lucas et al. [50] investigated frequency of changes in 28 office buildings over a period of 47 months. Moreover, they classified them into different types of changes. An extract of their results for office buildings is shown in Table 6. "The average number of changes per site-year can be interpreted as the percentage of buildings of a specific type that could be expected to undergo changes of the type identified each year if the changes are assumed to be randomly distributed across buildings" [50]. In reality, some buildings change more frequently than others. For example, the number of changes of the type *tendency,* within one building ranged from 0–2 times within the 4 years of monitoring. In general, changes in the occupancy, which include business type, tenancy, full and partial vacancy, involve major restructuring of the building and adaptation in the space layout design to fulfill the new space requirements. The relatively high frequency of these change types indicate the need for flexible office space designs. However, this study does not explicitly mention the lifetime of the space layout design. A detailed description of the lifetime of different parts of the building can be found in section 2.1.1.

Table 6. Frequency of changes in office buildings: percentage of buildings that undergo a change within one site-year (based on [50])

Type of change	Description	Frequency of changes per site-year
Business type	The business type change to another one. This involves a conversion of the space layout design.	1 %
Tenancy	The tenants change. This involves a conversion of the space layout design.	5 %
Full vacancy	The entire buildings becomes vacant.	10 %
Partial vacancy	Parts of the building becomes vacant.	11 %
Equipment	Equipment is changed, added or removed.	
	- Small pieces of equipment	32 %
	- Lighting	8 %
	- Heating/cooling equipment	6 %
Remodel	Structural changes in absence of other changes are done.	4 %
Unclassified load	A change in load is identified (not classified).	20 %
Electrical change	The electrical distribution system is changed.	1 %
Unclassified spike	A change in load for a short time is identified (not classified).	9 %

The overall frequency of change in office buildings is high in comparison to other building types [50]: "[…] 50% of the buildings experienced one type of change during the 2 years for which monitoring data were examined." Moreover, they found that larger, older office buildings tend to experience changes more frequently than smaller, newer buildings. Some types of change also have an impact on energy demand: *tenancy* is identified to have an influence on energy demand in all monitored buildings; *equipment* and *partial vacancy* have an influence on energy demand in most evaluated buildings.

In literature, no studies directly focusing on office space flexibility and its effect on thermal comfort and energy efficiency are found. Nevertheless, some studies compared different office space layout designs [53-55], performed parametric studies with office buildings to identify suitable building parameters [56, 57] or addressed the influence of the space layout design on energy demand in buildings in general [58]. These studies are presented in more detail in the following sections.

3.1.1 Flexibility in Office Space Design

Flexibility and adaptability is one criterion of the sustainable building certificate of the German Sustainable Building Council (DGNB) and includes the flexibility of the space layout design and the HVAC systems. "This criterion is aimed at making the building's design as flexible as possible and creating the greatest possible potential for conversion" [59]. Thus, a flexible building can easily be converted for another usage. Moreover, it is the second most important criteria for the economic quality of office buildings, accounts for 7.5 % in the total rating of a building and will become increasingly important. The highest score can be reached if no structural adjustments are necessary to change the systems. [59]

Many studies that focus on designing office buildings that fit the occupants' needs have been carried out. The studies presented in the following paragraphs use parametric models to identify the influence of the office space design on the building's performance, including energy efficiency and aspects of occupants' satisfaction, such as thermal comfort. Although some of these studies focus on aspects that are not central to this dissertation, such as the building envelope, their methodology is of high relevance.

Gratia and De Herde [56] conducted a parametric study to identify the design parameters that are most relevant to achieve an energy-efficient office building. They formulated generic guidelines and identified the most important influencing factors for the energy efficiency and indoor climate in office buildings. These factors are the building's insulation, internal gains from people, equipment and lighting, the size and orientation of the windows, ventilation of the space and the overall thermal inertia of the building's construction. As mentioned in [56]: "In an office building, the number of parameters influencing energy consumption and interior climate is very high." Thus, they showed that performing a parametric study to investigate the influence of several parameters are a suitable methodology for office buildings.

Moreover, a recent study [57] identified optimization potentials for office buildings, including the construction elements and envelope to reduce heating loads. This study uses a parametric approach to generate several design variants of the same office space and purpose, leading to design guidelines focusing on low-tech design strategies and robustness of energy demand and thermal comfort in summer. In addition, a brief comparison between a mechanical ventilation system and a radiant ceiling to cool the office space shows better result in thermal comfort, energy efficiency and robustness for the latter. As a conclusion, they suggest to use low-tech strategies as major optimization parameters and point out that "even the implementation of only one technical system creates a high degree of robustness with regard to the indoor climate conditions in the room" [57]. They define a design as "robust", if the building parameters change without a significant change in energy demand or thermal comfort. Moreover, they have also shown that a parametric approach is suitable for investigating office spaces. In this work, also the robustness of office spaces is investigated using a parametric model approach. However, the HVAC system configuration is investigated in more detail and the focus is on flexible space layout design and control zoning strategies, rather than on building parameters.

3.1.2 Influence on Energy Demand

While most studies developed approaches to optimize the more enduring parts of a building, such as the envelope, floor shape and fenestration, only few authors [58, 60] have addressed the potential of rearranging the more flexible space layout design.

This lack of studies could result from the finding [58] that using core/perimeter zoning, which is widely employed to divide a building model into thermal zones to perform a BPS, shifts the attention toward the envelope while the optimization potential of the space layout design is overlooked. The core/perimeter zoning, according to ASHRAE Standard 90.1 [33], divides the building in perimeter zones for each orientation and a core zone.

Dogan et al. 2015 [58] focused on the comparison of two different thermal zoning strategies for BPS. They compared BPS results derived from a model with the core/perimeter zoning with results from a model with a thermal zoning that strictly follows the space layout design of the building. They used 15 common types of residential and office buildings that differ in the following categories: ratio between circulation and used floor area, position of the circulation area and building shape. In general, 75 % of the results for the simulated energy use intensity (EUI) are with a $\pm$15 % margin when comparing the two thermal zoning strategies. Depending on the actual space layout design, different results are received: Cellular office spaces with slab shape generate smaller errors, because the zoning strategies are similar for this space layout design. One of the largest errors is obtained for the open-plan office spaces with slab building geometry. Moreover, large errors are obtained for variants where the unconditioned circulation area is at edge of the building and thus can serve as thermal buffer zone. In summary, they suggest that core/perimeter zoning should only be applied for early design evaluation when the actual space layout design is not known, otherwise “the efficiency improvement potential of the floor plan layout itself is overlooked” [58]. Therefore, a *fine-grained* thermal zoning is suggested to investigate the different space layout designs, especially for open-plan offices. To explore the potential of optimizing the space layout design Dogan et al. [58] performed a brief proof-of-concept study. They simulated one floorplan with nine different space layout designs that have different position and sizes of an unconditioned circulation area and found that the space layout design has a significant influence on energy demand.

Musau and Steemers [54] investigated the impact of space layout design and occupancy rate on the energy demand in office buildings. They considered five typical office space layouts and the level of occupancy ranges from 25–100 % occupancy rate. As a result, their “[…] analysis demonstrated that space planning and utilization have significant impacts on energy use and are important in assessing energy performance.” The cell and the combi office type, which are described in section 2.1.3, show a good match between energy demand and occupancy rate. However, the most energy-efficient space layout design is the open-plan office or mixed layouts rather than closed space layout designs such as the cell office type. They did not investigate a changing space layout design in terms of flexibility but point out that the importance of continuous adaptations since the office space changes frequently.

3.1.3 Influence on Thermal Comfort

Another relevant aspect besides energy demand, especially in office buildings, is thermal comfort. Thermal comfort is one part of the indoor environmental quality (IEQ), which also includes indoor air quality, visual and acoustic comfort. Wagner et al. [15] remarks that occupants’ satisfaction with the IEQ also has an effect on their motivation and performance. Taking into account that the personnel costs in companies are clearly above all other costs for the operation of the building, it is of great relevance to consider IEQ when designing a building. [15]

Al horr et al. [61] confirms the link between IEQ and occupants well-being and satisfaction. Therefore, IEQ should be considered at an early design phase of a building. “Literature suggests that green building designs don’t automatically guarantee that the building designed will be comfortable and ensure occupant well-being” [61]. This statement underlines the importance of considering both aspects, thermal comfort and energy efficiency, in office space designs.

However, only few publications [53, 55] correlating the choice of office space layout designs to the resulting occupants' thermal comfort level are found in the literature. Moreover, no publications have been found that use the same office floor plan to investigate the effect of different space layout designs on its thermal comfort and energy demand. Thus, the flexibility of space layout design is not investigated in details.

Shahzad et al. [55] compare two different office space layouts with low and high level of controllability of the thermal environment. One is a cellular office building in Norway with individual controllability of heating, cooling, blinds, windows and air conditioning to ensure indoor air quality. The other is an open-plan office building in England with a low level of thermal control and centrally operated displacement ventilation. The level of controllability may be equated with the number of control zones in an office space. They conducted a survey with the occupants and found that the Norwegian office had a 35 % higher occupants' satisfaction and 20 % higher thermal comfort compared to the British office. In both offices, the IEQ was in acceptable range. This is why they conclude that the non-availability of thermal control was the main reason for discomfort, which in turn is not necessarily due to the different space layout design. This result indicates that the number of control zones might have an influence on thermal comfort. However, the energy demand in the open-plan office was much lower the energy demand in the cellular office. "Overall, a balance between thermal comfort and energy efficiency is required, as either extreme poses difficulties for the other" [55].

Not only thermal comfort and energy efficiency are important performance indicators in office spaces, but also financial aspects, which are directly connected to space usage, play a major role in choosing a suitable office space layout design. In this context, Saari et al. [53] studied the effects on overall costs of an office building in Finland when the area per person is increased. They take into account indoor climate as well by assuming to have a loss of productivity of the occupants if the indoor climate is not comfortable (temperature higher than 25 °C), according to [62]. Moreover, they assume that too low ventilation rates and too high occupant density leads to sickness and thus short-term sick leave, according to [63]. "The results of this study suggest that an improvement in the quality of indoor climate is cost-effective when its economic impact on health and productivity are taken into account in addition to the investment, operation and maintenance costs" [53]. Moreover, they found that the "conversion to cell offices was most expensive, while the conversion to open-plan offices was the cheapest, especially when the quality of the indoor climate was high" [53].

3.1.4 Summary

- The frequency of change in office building is high in comparison to other building types: on average one type of change occur within 2 years.
- In office buildings, tenants change frequently. This can be one of the reasons why the space layout design need to be changed every 3–7 years.
- No studies have been found that focus on the influence of a flexible space layout design on thermal comfort and energy demand in office spaces, even though flexibility is identified as one important criterion for sustainable buildings.
- A parametric model approach has been proven to be effective in investigating changes in boundary conditions and to identify *robust* design parameters for office spaces.
- Only few publications investigated the influence of the space layout design on energy demand, because the most commonly used thermal zoning strategy (core/perimeter zoning) shifts the attention towards the envelope. However, differences in energy demand occurred are mainly due to the different space usage, rather than the differences in the actual space layout design.
- Thermal comfort is important for the occupant's well-being and satisfaction and especially for motivation and performance at work.
- The influence of space layout design on thermal comfort in office buildings has not been investigated in detail.

Therefore, there is a need for flexibility in office space design to be able to react to changes and guarantee thermal comfort during the entire operation phase. Moreover, the influence of space layout design on thermal comfort and energy demand needs to be further investigated.

3.2 Robust HVAC System Design and Control

The actual energy demand of a building in operation can be up to 2.5 times the energy demand calculated with a BPS. This difference is the so-called performance gap and occurs especially in the first year of operation and after interior renovations. [5] Even though there have been several efforts to close the performance gap, the possibility to react to an undesired building performance during the operation phase has not been investigated in detail. To be able to make adjustments for simultaneously maintaining energy efficiency and high thermal comfort and to react to unpredictable events, the HVAC system needs to be flexible. "Therefore, future research on improving the flexibility of building system is recommended" [5].

An HVAC system design that is robust can be adapted to several prevailing indoor climate conditions without compromising in thermal comfort or energy efficiency. Especially in office buildings, robust HVAC systems are necessary because of the frequently changing boundary conditions. This dissertation raise the question which HVAC system configuration provides a *robust* solution for a flexible office space and how its control zones should be designed.

In this section, different HVAC system configurations and control strategies that have been investigated in office spaces are presented.

3.2.1 HVAC System Comparison

In the following, studies that compared different HVAC systems in terms of their performance in office buildings are presented.

In an extensive study [64] on office buildings in Europe, strategies to reduce CO_2 emissions are investigated. They performed an energy analysis based on actual monitored building data. "One of the reported findings is that the type of the HVAC system significantly influences total energy consumption" [64], which reflects the importance of HVAC system design.

Olsen and Mattarolo [65] have evaluated and compared different HVAC system configurations for the use in office buildings and found that radiant systems generate better results in thermal comfort and energy efficiency than conventional air conditioning systems.

In a recent study, Talami and Jakubiec [66] compared TABS and two types of radiant ceilings in terms of energy demand and comfort and found that radiant ceilings represent a feasible solution because of their low thermal inertia and fast response. The results are based on a BPS with a parametric model of an office building in Singapore. They identified the selection of the set point temperature, as well as the solar heat gain coefficient and window-to-wall ratio as crucial to achieve a good building performance.

Moreover, Korolija et al. [67] compared three mechanical ventilation systems for a cellular and an open-plan office in England. The systems are a centralized variable air volume and a fan coil system with heat recovery unit and a fan coil system without heat recovery. They found that the energy demand of individual zones within the building strongly depends on the distribution of the internal gains. “This study showed that even for the same activity (office), the difference in internal gains for open plan office arrangement and cellular office arrangement has significant implications for cooling and heating energy” [67], whereby open-plan offices showed higher energy demands. Moreover, a variable air volume system has a lower energy demand than the fain coil system used in in the open-plan office. However, if a fan coil system with heat recovery is installed instead of the fan coil system without heat recovery around 70 % of the heating energy demand can be saved. “The energy performance of an HVAC system depends not only on its configuration and operational parameters, but also on the characteristics of the heating and cooling demand of the building” [67]. In their study, one thermal zone is considered for the open-plan office, considering a homogenous room climate in this space. However, this assumption of a homogeneous room climate is often not fulfilled in reality. To consider this, the control zoning strategy of the HVAC system is important and will be explained in more details in the next section.

3.2.2 Control Zoning

To guarantee thermal comfort in office buildings, it must be possible to adjust the HVAC system according to the prevailing indoor climate conditions. This ability to control the indoor climate depends on the control zoning strategy of the HVAC system, because a control zone defines the area in a building that can be controlled individually [68]. Smaller control zones result in more controllability of the indoor climate conditions. The size of a zone can range from a portion of room (referred to as “fine-grained zoning”), over a room (referred to as “room-based zoning”) to a whole floor (referred to as “floor-based zoning”). A recent development are personal control systems for ventilation and thermal comfort, where each workstation is a separate control zone and the climate conditions can be controlled individually by the occupants. In general, it can be said that “[f]ewer zones will result in some level of discomfort. More zones than necessary will increase the first cost of the project” [68]. Moreover, more zones will also increase the complexity. However, the aim of control zoning is always to be able to respond to changing thermal conditions and maintain a high indoor environmental quality. Thus, a compromise has to be found. Moreover, the timing of loads typically influences zoning decisions in a room. “As an example, an east-facing office must be zoned separately from a west-facing office due to solar radiation patterns” [68].

The process of dividing a building into thermal zones must be done before the HVAC system is planned in detail. In most cases, the defined thermal zones are then treated as control zones to control the passive and active systems in the building. Grondzik and Kowk [68] emphasize that each thermal zone "[...] must be provided with separate control if thermal comfort expectations are to be met".

Shin and Haberl [35] summarized that the literature provides a set of criteria to zone a building for HVAC system control. These criteria are solar gains, orientation, occupancy and their schedule and space usage. However, no systematic approach that can be applied to any building is available.

Bres et al. [69] emphasize the significance of control zoning to evaluate both thermal comfort and energy demand. In their study, they distinguished between control zoning and thermal zoning to prepare a building model for the BPS. They found that the thermal zoning should be finer than the control zoning to evaluate load differences that could occur, because of a too coarse control zoning. In addition to the differences in heating and cooling load, differences in thermal comfort should also be taken into account. "However, these differences can be expected to vary significantly with HVAC system, control scheme and sensor location" [69]. This implies that depending on the HVAC system that should be evaluated, different level of detail of the thermal zoning should can be applied. Bres et al. investigated different residential floor plans and found that comfort violations increases with a coarser control zoning. Here, the temperature in the zone is up to 30 % of the time outside the comfortable climate conditions. However, the amplitude of errors vary strongly depending on the studied floor plan, this is why a separate investigation for each space layout design is recommended. As a result, they found that control zoning and internal gains have a high influence on their results for thermal comfort and energy demand.

As mentioned in section 3.1.3, Shahzad et al. [55] confirm this result with their findings that the level of controllability and thus the number of control zones has an significant influence on the occupant's thermal comfort.

An extreme case for a very fine-grained zoning is personal ventilation. Here, the air conditioning operates on a workplace-specific level. To realize this, in [70] personalized ventilation systems with radiant ceiling are compared with a mixed ventilation system for an office room with two occupants. They found that radiant ceiling with personal ventilation provide enough fresh air and thus can maintain good indoor environmental quality.

3.2.3 Control Parameters

Not only the size and position of the control zones have an influence on energy demand and thermal comfort in the building. The parameters that are used to control the HVAC system are equally important. Several studies have investigated the influence of parameters, which are taken into account in the building control on the buildings and HVAC system performance. Especially, the selection of the controlled variables [71], input parameters [72] and temperature set points [73] seem to have a significant impact in office buildings. Moreover, the consideration of disturbances such as occupants' behavior and their spatial distribution [72, 74] are crucial for the performance of the controller.

Wang et al. [74] used a neural network algorithm to estimate the spatial distribution of occupancy and used this information to control an HVAC system. This study showed the importance of occupancy information, because they obtained 20 % energy savings in a traditional open-plan offices.

Applying the concept of a fine-grained control zoning, Nagarathinam et al. [72] addressed the energy saving potential considering the spatial distribution of the mean radiant temperature in open-plan offices to control air handling units (AHU). Even if the air temperature in an open-plan office is relatively constant over the whole space, the mean radiant temperature can differ significantly. This is mainly due to the distribution of direct solar radiation: radiation entering the space through windows heats up the surfaces it reaches within the building, resulting in a higher operative temperature in those areas. The proposed predictive control method, which uses the mean radiant temperature and occupancy distribution as known inputs, achieves energy savings up to 21 % compared to a baseline PID controller, which only uses thermostats measurements and has no information about the occupancy distribution. The new control strategy "[…] give[s] additional savings of 7 % by maintaining regions at different set-points within the acceptable comfort limits based on the non-uniform spatial MRT [mean radiant temperature] information alone" [72]. In their study, only AHU are investigated and the size and position of the control zones are not varied.

Wang et al. [71] considered the operative temperature in office buildings as the controlled variable for different HVAC systems. They simulated an office space with a mechanical ventilation (MV) system, a thermally-active building system (TABS) in the floor and a radiant ceiling (RC) for heating and cooling in Denmark, France and Italy. They obtained different results depending on the used HVAC system: If an MV is controlled based on the operative temperature, better results for the thermal comfort can be generated. However, this leads to a higher energy demand. For the radiant systems, TABS and RC, the opposite is the case. They suggest that in north-facing office spaces an air temperature based control should be used for MV systems and an operative temperature based control for RC and TABS. For the south-facing office spaces, only an operative temperature based control is recommended for all systems. The results indicate that the control strategy should be based on the specific boundary conditions in the office space, such as location of the investigated area, the space layout design and the HVAC system, and is difficult to generalize.

Aryal and Becerik-Gerber [73] investigated comfort-driven temperature set points in office buildings. Their aim was to identify the impact of zone level set points instead of a centralized HVAC system control, which usually overlooks the thermal comfort preferences of occupants. The comfort set points are obtained from 400 comfort profiles and they “observed that setting zone level setpoints can increase occupant satisfaction compared to building level setpoints” [73]. This implies that a more fine-grained control zoning results in a higher occupant satisfaction. Compared to a fixed building level set point of 22.5 °C, the occupants’ satisfaction increased on average by 25 % and the energy consumption decreased by 2.1 %. Compared to set point temperature of 24 °C for cooling and 21 °C for heating, the occupants’ satisfaction increased on average by 40 % and energy consumption increased by 6.2 %. “In other words, although the zone level set points are set based on occupant preferences, it was not possible to satisfy the requirements of all occupants. This is one of the limitations of using centralized HVAC systems in buildings because the entire zone is controlled at the temperature around the setpoint for that zone and occupants whose comfort range lies far away from the setpoint cannot be satisfied” [73]. As a result, they recommend personalized comfort systems that operate on a detailed level.

3.2.4 Summary

- The HVAC systems need to be flexible, to be able to make adjustments during the building's operation and to react to unpredictable events. In addition, a flexible HVAC system can help to react to the performance gap, which typically occurs in the first years of operation or after interior renovations.
- The HVAC system should be robust enough to guarantee thermal comfort and an energy-efficient operation under changing boundary conditions, such as different usages and/or changes in the space layout design.
- An extensive literature search revealed that there are no related studies, which addresses the applicability and robustness of different HVAC systems in flexible office spaces in terms of thermal comfort and energy efficiency in literature.
- The comparison of different HVAC system configurations in office buildings shows great potential for radiant ceilings and recommends mechanical ventilation in particular with heat recovery. However, the actual performance of the HVAC systems depends strongly on the usage of the office space.
- In general, the HVAC system design has a significant impact on the energy demand and indoor environmental conditions in office buildings.
- The definition of the control zones has a significant influence on the performance of the HVAC system, especially few control zones that imply less controllability of an office space, can result in discomfort.
- The spatial distribution of occupants and the mean radiant temperature in office spaces are important to consider in the control strategy.
- Different control strategies or more precisely the number of control zones and the controlled variable are required for different HVAC system configurations. However, no extensive study on the correlation between the configuration and the number of control zones that should be selected to guarantee thermal comfort and an energy-efficient operation have been done so far.

Thus, further research on the correlation between HVAC system design, which includes the system's configuration, its control zoning and the controlled variable, and a flexible space layout design in office spaces is necessary to generate robust solutions in terms of thermal comfort and energy efficiency.

3.3 Developments in Thermal Zoning for BPS

One way to evaluate the performance of a building including the HVAC system design is a building performance simulation (BPS). For this purpose, the building model needs to be separated in different thermal zones to calculate energy balance for each zone. The air in a thermal zone is assumed to be perfectly mixed, thus the climate conditions in a thermal zone accounts for the whole volume combined by the zone.

Moreover, thermal zoning for BPS and control zoning for HVAC systems cannot be strictly separated, because they follow the same rules and purposes. For example "[…] facility managers can use zoning at an operational level, by deciding how to use the rooms available in order to mitigate the impact of a warmer climate" [75]. Thus, the presented concepts of thermal zoning can also be related to control zoning. As mentioned in the previous section, in order to evaluate control zoning strategies, the thermal zoning of the building model plays a crucial role.

In this chapter, literature on the definition of thermal zones for the thermal simulation of office buildings and their influence on energy demand and thermal comfort are summarized. This is also relevant for the control zoning of HVAC systems and the development of the approach presented in this dissertation.

3.3.1 Defining the Zonal Resolution

The issue of zonal resolution for thermal building models has been addressed in various contexts. The zonal resolution defines the way a building is separated into zones, which includes the total number of zones, the size of each zone and their location in the building.

In general, the method of thermal zoning for the BPS varies according to the level of knowledge about the building. It is distinguished between the conceptual design phase when the actual space layout design is unknown and the detailed design phase when the actual space layout design is defined already. In conceptual design phase, the ASHRAE standard [33] recommends to separate a building's floor in one perimeter zone for each orientation and one core zone (referred to as "core/perimeter zoning"). In this phase the HVAC system configuration and control zoning is also defined. As mentioned before, Dogan et al. [58] criticize this simplified method, as it draws the attention to the building's envelope and may overlook the improvement potential within the building. They developed an algorithm that automatically divides a building model in thermal zones according to the core/perimeter zoning to accelerate the modelling process for urban scale analysis. In the detailed design phase, in which the space layout design is known already, different thermal zoning approaches are applied, than in the conceptual design phase. A common approach is to separate each room in one thermal zone (referred to as “room-based zoning”) and group zones with similar behavior.

Moreover, it is important to mention that the process of dividing a building into thermal zones is based on the modeler’s experience and thus is not consistent across all building energy models. Thermal zoning is used to reduce the models complexity, but also the accuracy of the results is reduced “when dissimilar regions of a building are defined by a single zone” [76]. As one consequence, a building model’s behavior typically differs from the real building, which is then called performance gap, as mentioned before.

As summarized in Shin and Haberl [35], the criteria mentioned in the literature for thermal zoning for HVAC system design are solar gains, orientation, occupancy and their schedule and space usage. Those are the same as for control zoning mentioned in the previous section. The authors give an extensive overview of thermal zoning strategies for BPS. Most reviewed studies focus on the traditional *core/perimeter* zoning rather than developing a new thermal zoning method. As a result, the study indicates that there is a significant variation in simulation model output and accuracy based on selection of the zoning method. “Future work should identify the buildings features most likely to have a great impact on thermal zoning” [35].

Only few publications define a method for thermal zoning applicable to various buildings. In this context, Georgescu and Mezić [76] uses the Koopman operator to identify areas of the building with the same thermal behavior and thus identify the optimal size and position for the thermal zones. Shin [77] presents a new method to define thermal zones using a grid structure within in the building. In his work, different thermal zoning methods are investigated and their correlation to the simulated energy demand is presented. The building shape, the window-to-wall ratio, the window orientation and the climate condition are identified to have an impact on the thermal zoning approach. The number of thermal zones per floor, which Shin investigated, range from 1–12 zones. However, no internal loads are considered and no HVAC systems are simulated.

3.3.2 Influence on Energy Demand

The following studies investigated the correlation between thermal zoning and energy demand.

Beil De Souza and Alsaadani [78] investigated a speculative office building in London, with three different thermal zoning strategies: floor-based zoning with one zone for the whole floor, core/perimeter zoning and room-based zoning according to the space layout design. They found that “the zoning strategy seems to be influencing the results as much as the different internal gains and ventilation rates” [78]. Especially, the *core/perimeter* zoning underestimated the heating energy demand and overestimated the cooling energy demand compared to the more detailed *room-based* zoning. They conclude that the thermal behavior of a thermal zone is mainly influenced by the floor area, the window area and the internal gains. Moreover, they emphasize that more simulations are necessary to establish thermal zoning criteria for building models.

Jiangshan et al. [79] investigated different simplification methods for thermal buildings models. One simplification is the number of thermal zones. In this context, three thermal zoning strategies were compared. As a result, a difference of 32 % between the energy demand obtained from a model with floor-based zoning and a model with room-based zoning according to the space layout design is achieved .

As mentioned in the previous section, Bres et al. [69] addressed the issue of thermal zoning methods and conducted a case study with different control zoning strategies for apartment buildings. They suggest using a fine-grained thermal zoning of building models to quantify control inefficiencies due to too coarse control zonings.

In summary, all mentioned studies confirm that the zonal resolution has an influence of the calculated energy demand of a building. Moreover, Dogan et al. [60] also found that depending on number of thermal zones the EUI deviates up to 8 %. In addition, they emphasize the importance of the boundary condition between the thermal zones. This boundary condition can be derived from the space layout design and includes the heat and/or mass transfer between two zones. As an example, the boundary condition can be defined as adiabatic or a combination of conduction, radiation and/or interzonal airflows. Compared with a single zone where the air is perfectly mixed, the different boundary conditions result in a variation of the annual heating energy demand of 41 % and annual cooling energy demand of 10 %. This implies the importance of the space layout design on the heating and cooling required in the thermal zones, because it defines the boundary conditions between the zones. A previous study on solar houses [80] confirms this findings, because they found that thermal zoning and interzonal airflows can have significant impact on the predicted energy demand and thermal comfort. The authors show that building models with a coarse thermal zoning can underestimate energy demand and the level of thermal comfort.

3.3.3 Influence on Thermal Comfort

While most studies focus on energy demand, like mentioned in the previous section, only little attention has been paid to the impact of thermal zoning on thermal comfort in office spaces. In this context, De Wilde and Tian [75] identify the need for designing more flexible indoor environments to reduce the risk of overheating and emphasize that the thermal zoning of the building model has a significant effect on the predicted thermal discomfort. In their study, an office building is modeled with two different zoning strategies and is simulated during summer months to evaluate the overheating risk. They focus on how the BPS should be adapted to provide a reasonable tool for investigating the building's behavior under climate change. As a result, they identified "[…] that the choice of [thermal] zoning method may have a significant influence on the predicted overheating risk and work performance under climate change" [75]. To investigate the energy demand a coarse thermal zoning, such as floor-based zoning or core/perimeter zoning, is sufficient, because the main impact factor are internal gains. However, these thermal zoning methods hide deficiencies in individual rooms. This is why for investigating the overheating risk or the thermal comfort a thermal zoning method oriented on the actual space layout design is suggested. They obtained different levels of thermal comfort in the thermal zones on the same floor. To deal with this issue the authors suggest "[…] to design more flexible indoor environments which allow repositioning occupants and office equipment" [75].

To model the indoor environment at an workplace level, Wagner et al. [15] remark that the calculated average temperature for a thermal zone may not reflect the actual thermal comfort conditions at a workplace near a window. Depending on the quality and size of the glazing, the local operative temperature can differ. Effects such as one-sided radiation or heat exposure due to solar radiation are not taken into account.

As illustrated in our previous study [81], office space requires assessment on detailed level in order to evaluate thermal comfort and energy demand for a modern open space office. This dissertation is based on this principle and uses a *fine-grained* thermal zoning to investigate different control zoning strategies in a flexible office space.

3.3.4 Summary

- The methods for thermal zoning for BPS can also be applied for control zoning of HVAC systems. Nevertheless, only few studies have investigated the correlation between thermal zoning and control zoning for different zonal resolutions of those two.
- A distinction between thermal zoning for an unknown space layout design in the conceptual design phase and a known space layout design in the detailed design phase needs to be done.
- Using only few zones, such as core/perimeter zoning or floor-based zoning, draws the attention to the building's envelope and overlooks the potential of the space layout design to improve the building's performance.
- The boundary conditions between thermal zones have a significant influence on the energy demand of the zones. These boundary conditions are derived from the space layout design. Thus, thermal zoning should be based on the space layout design.
- A coarse thermal zoning is suitable for determining the energy demand in conceptual design phase, but it hides deficits in individual rooms and areas of the office space. Thus, for the investigation of thermal comfort and control zoning strategies a fine-grained zoning should be selected.

In summary, a *fine-grained* thermal zoning is necessary to evaluate thermal comfort in flexible office spaces, in particular the control zoning strategies and the space layout design. Moreover, the space layout design should determine the boundary conditions between thermal zones.

3.4 Contribution of this Dissertation

In the following, the key points from the literature reviewed in sections 3.1–3.3 are summarized. They are relevant to understand the context and motivation of this dissertation. Afterwards, the gaps in the reviewed literature are highlighted and the contribution of this dissertation is presented.

Key Points from the Reviewed Literature

- In office buildings, the space layout design needs to be changed every 3–7 years and, on average, one type of change occurs every 2 years. Therefore, there is a need for flexibility in the office space design to be able to efficiently react to changes and guarantee thermal comfort during the entire operation phase of a building.
- Space layout design seems to have a significant impact on the calculated energy demand in a thermal zone and on its thermal comfort.
- The HVAC system should be robust enough to guarantee thermal comfort and an energy-efficient operation under changing boundary conditions, such as different usages and/or changes in the space layout design.
- The definition of the control zones has a significant influence on the performance of the HVAC system. For example, the definition of too few control zones can result in discomfort for certain HVAC systems, because this implies less controllability of the office space. Thus, the control zoning strategy needs to be defined individually for each HVAC system configuration.
- A fine-grained thermal zoning is necessary to evaluate the thermal comfort in flexible office spaces. Moreover, the space layout design should determine the boundary conditions between thermal zones.

As a result, the reviewed literature suggests that a more detailed understanding of flexibility in office spaces, including a flexible space layout design and a robust HVAC system design, represents an untapped improvement potential for performance-based building design.

Gaps in the Reviewed Literature

- The influence of the space layout design on thermal comfort in office buildings has not been investigated in detail.
- In the literature, the applicability and robustness of different HVAC systems in flexible office spaces in terms of thermal comfort and energy efficiency has not been addressed.
- Further research on the correlation between the HVAC system design, which includes the system's configuration, its control zoning and the controlled variable, and a flexible space layout design in office spaces is necessary to generate robust solutions in terms of thermal comfort and energy efficiency.
- No approach to model and evaluate flexibility in office spaces is published. This includes the following:
    (1) Modelling a flexible space layout design and the consequences for thermal comfort and energy demand in office spaces.
    (2) Supporting decision making on HVAC system configuration and their control zoning strategy in the conceptual design phase when the space layout design is not known exactly.
    (3) Supporting interior renovation decision making, which could be beneficial if one of the design parameters should be renovated without changing the rest. For example, when the position of a meeting room should be changed without changing the HVAC system or the control zoning or vice versa.

In summary, it can be said that in particular the correlation between the topics mentioned and their application in flexible office spaces is not addressed in the literature. These gaps in the reviewed literature coincide with the objectives of this dissertation, defined in section 1.2.

Contribution of this Dissertation

The main contribution of this dissertation is the proposal of a methodology that enables an *office space design for flexibility* by correlating the space layout and the HVAC system design, including its configuration and control zoning strategy. These correlations, illustrated in Figure 11, are investigated with the aim of achieving flexibility, thermal comfort and energy efficiency in the office spaces. A BPS with a fine-grained thermal zoning is used for this purpose, as recommended in the reviewed literature.

As a result, it is expected that the comprehensive understanding of the correlation between these design parameters will enable an office space design for flexibility in the future.

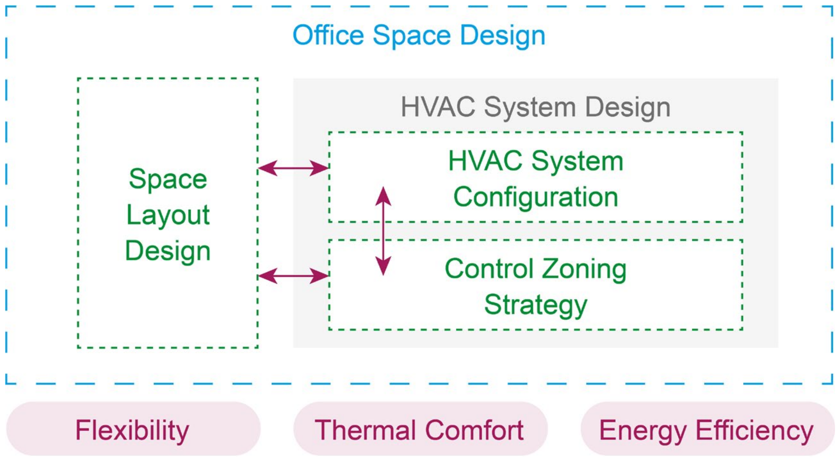


Figure 11. Contribution of this dissertation

4 Building Modeling Methodology

In this chapter, the building modeling methodology to develop an *office space design for flexibility* is described in the following order: First, a general description of the approach to model flexibility in office spaces is presented. It includes the definition of disturbances, constant and flexible design parameters, the setup of the parametric building model and the thermal building simulation. In the latter, the definition of thermal zones, airnodes and their boundary conditions are described. Moreover, the software framework, which is used to implement the approach, and the assumption and simplification that are made, are presented.

Second, a case study with a speculative office space is investigated to show the feasibility of this approach. In addition to presenting the detailed characteristics of the building model, which is based on a typical modern open-plan office, a detailed description how to apply the proposed approach is given. Finally, the HVAC system design, including the HVAC system configuration and its control strategy, is presented. It is noted that certain aspects of this case study were published in [82].

4.1 General Approach: How to Model Flexibility?

In this dissertation, an approach to model flexibility in office spaces is developed. Initially, the parameters that change most frequently in office space are identified based on the existing literature. During an office building’s life cycle, the space layout design and the HVAC systems change most frequently, as described in section 2.1.1. Thus, the presented approach models the space layout design, the HVAC system configuration, the control zoning strategy and the controlled variable as *flexible* design parameters.

The overall concept of the approach is illustrated in Figure 12 and can be described with four steps, which are explained in the following section. This approach is then applies in a case study to a modern office space, as described in sections 4.2–4.2.5.

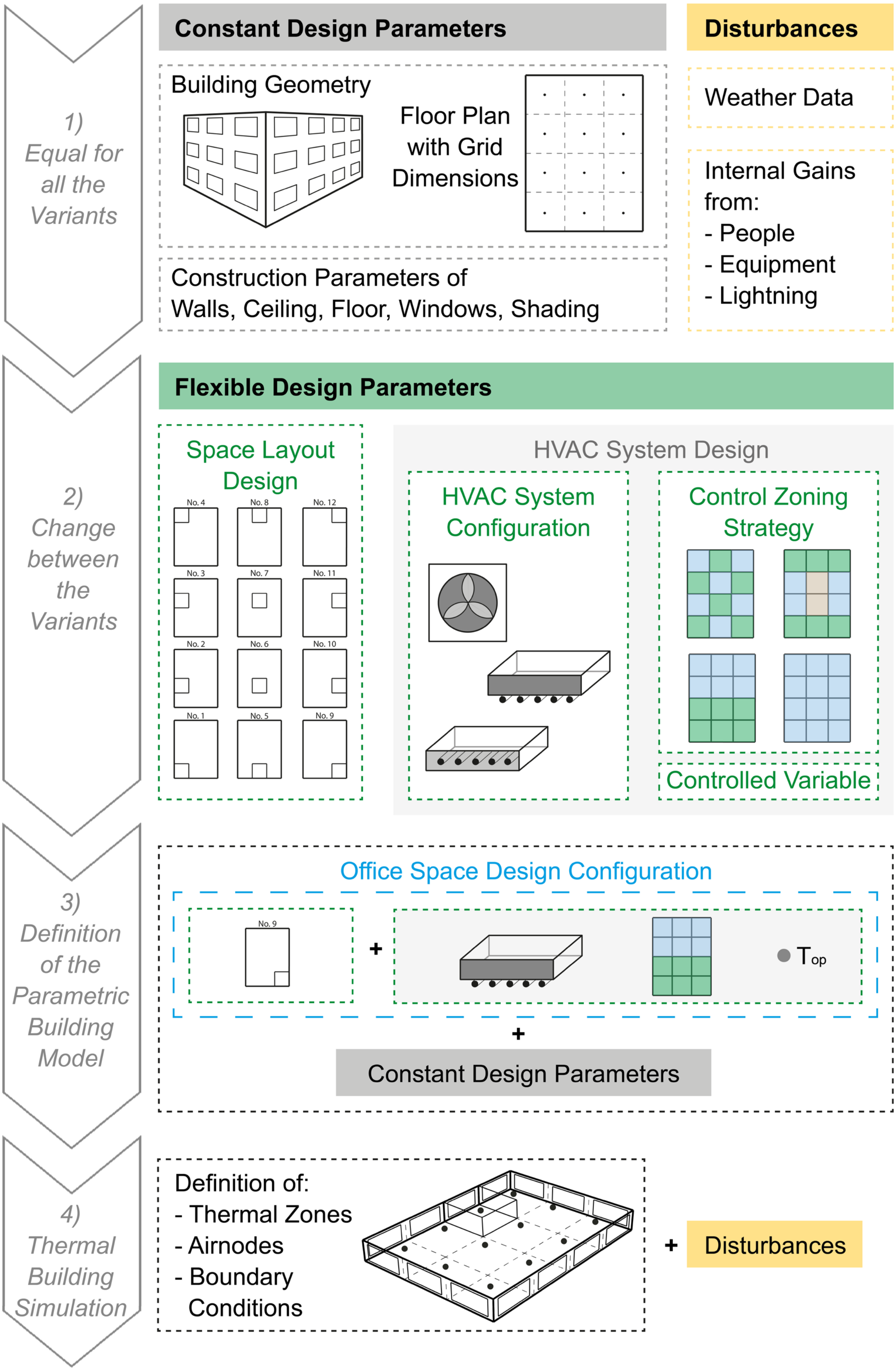


Figure 12. Approach to model flexibility in office spaces

4.1.1 Parametric Building Model

In this section, the first three steps of the approach are described, resulting in the definition of the parametric building model. To model a flexible office space, a distinction is made between inputs that are equal for all variants of the office space (Figure 12.1) and those that change between the variants (Figure 12.2).

Constant Design Parameters

In the first step, all parameters that are assumed to be equal for all variants of the building model are defined.

The constant design parameters are the building's orientation and exterior geometry, including the façade grid that defines the dimensions of the possible space layout. Employing a building model with design parameters that are constant for all variants allows to investigate the influence of the *flexible* design parameters on thermal comfort and energy demand in an isolated manner.

Disturbances

Additionally, the disturbances that are equal for all variants are the internal gains from people, equipment and lighting in the office space. This includes the related schedules, which define the time period in which the internal gains occur. Moreover, the weather data and accordingly also the location are equal for all variants.

Flexible Design Parameters

In the second step, the parameters that can be changed in the building model are defined as flexible design parameters, which include the space layout design, the HVAC system configuration, the control zoning strategy and the controlled variable, whereas in this work the last three are treated in combination under the term "HVAC system design".

A typical method for designing the space layout is according to the façade grid, which is defined by the building's geometry and structural design, as described in section 2.1.3. Interior drywalls can be installed along the grid structure and thus form different space layouts. In this case, a finite number of different space layout designs can be generated using this grid structure. The number of possible space layout designs determines the number of variants.

Moreover, since the HVAC system design is frequently changed in office spaces, it is considered as a flexible design parameter in this approach. Therefore, different HVAC system configurations, control zoning strategies and controlled variables can be selected to be evaluated in a flexible office space.

Office Space Design Configuration

If one option of each flexible design parameter is selected, a complete *office space design configuration* is defined, including one space layout design, one HVAC system configuration, one control zoning strategy and the controlled variable. An example of such a design configuration could be composed of space layout design no. 1, mechanical ventilation and fine-grained control zoning, controlled according to the operative room temperature.

Definition of the Parametric Building Model

The third step is to combine the constant design parameters with the selection of the office space design configuration to generate a complete building model that can be simulated. The flexible parameters are parametrically defined and can easily be changed in the building model, as described in section 2.3.3. Therefore, all design variants can be simulated in an automated manner with a low manual effort using the parametric building model. By coupling the parametric building model with a thermal building simulation, it is possible to evaluate the office space design at a detailed level.

4.1.2 Thermal Building Simulation

The fourth step is to use the parametric building model of each variant to setup and run a thermal building simulation over the period of 1 year.

Definition of Thermal Zones and Airnodes

The thermal zones for the thermal building simulation are defined according to the space layout design. Each room is represented with one thermal zone but can contain more than one airnode depending on the size of the room. The thermal zones are used to calculate the radiation balance, as described in section 2.3.3, whereas, each airnode is used to calculate the energy balance of the space it is representing.

The total number and the size of the airnodes depends on the width and the length of the building and its façade grid, and does not change when the space layout design is modified. Moreover, it is assumed that each grid element defines the dimensions of one airnode. For instance, if the building is three grid elements wide and four grid elements long, the thermal building model consists of 12 airnodes, as shown in Figure 13. Here, the small room in the corner consists of one thermal zone with one airnode and the large open-space consists of one thermal zone with 11 airnodes.

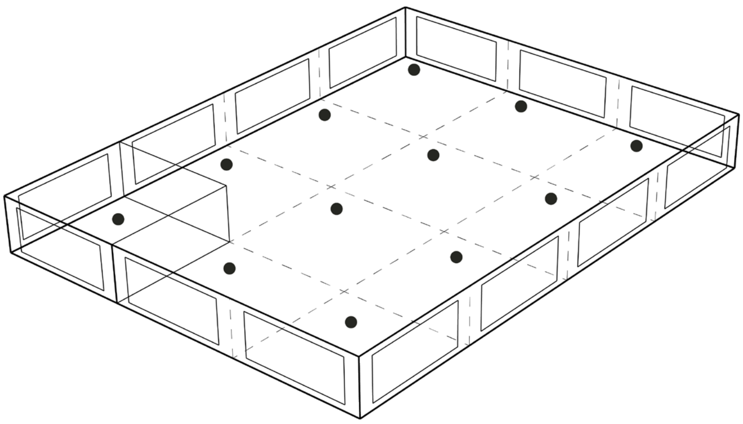


Figure 13. Definition of thermal zones and airnodes

Boundary Conditions of Airnodes

The boundary condition between adjacent airnodes depends on the physical layout in the building. In this work, also the boundaries of the thermal zone are equal to physical space layout in the building. Airnodes that are within the same thermal zone are coupled with a bidirectional airflow to model the air exchange within the room. If adjacent airnodes belong to different thermal zones, and thus rooms, an adjacent interior drywall is defined instead of a coupling airflow. The temperature of the drywall between two airnodes is calculated with the temperature differences between the airnodes and the heat transfer through this wall, thus results in a heat transfer between these airnodes. These boundary conditions are adapted automatically when the space layout design is changed.

Zonal Resolution

In contrast to the traditional approach, which uses only one airnodes to assess a room, this approach uses multiple airnodes to evaluate thermal comfort and energy demand on a detailed level. This decision is based on previous research published by the author [81], where an office space with eight airnodes is modeled to investigate the effect of the space layout design and control zoning strategies on thermal comfort and energy demand. The results indicate that the zonal resolution is a crucial factor in the process of assessing the thermal comfort in flexible office buildings. To design an office space layout that avoids discomfort in an individual area, the selection of a sufficiently high zonal resolution in the thermal building model is suggested. Therefore, the thermal zoning of the building model should be fine-grained in this approach, whereas the façade grid dimensions determine the size and position of the thermal zones.

Unlike the thermal zoning, the control zoning of the HVAC system (also called HVAC zoning, as described in section 2.3.1) is a flexible parameter in this approach. The zonal resolution of the control zoning can be determined using the methodology presented in this section. In the literature, only few publications address this question, a summary of which can be found in section 3.2. According to Bres et al. [69] “a simulation zoning finer than the HVAC zoning […] can be assumed to give more accurate results. In particular, it may allow the control inefficiencies deriving from a coarse HVAC zoning, i.e. local overheating or underheating, to be quantified.”

The steps one to four are described in more detail in the case study in the sections 4.2–4.2.5. The research results for the case study are presented and discussed in chapter 5.

Assumptions and Simplifications

In this work, a software framework as described in section 2.3.4 is used. Once all input files are generated using TRNLizard, the thermal building models of all design configurations are automatically simulated with TRNSYS 18. Finally, the generated output data is than analyzed using a Matlab script [83].

In the thermal building simulation, some assumptions and simplifications are made, which are listed below.

- The air within one airnode of the building is well-mixed, resulting in a uniform temperature in the complete airnode
- The infiltration through the building’s envelope does not vary due to outside weather conditions.
- The influence of neighboring buildings or objects on the simulation model, for example regarding the reduction of solar gains, is not considered.
- The schedule of the internal gains does not consider public holidays nor seasonal variations in the occupancy. Instead, it only differentiates between weekdays and weekends, each of which have the same schedule throughout the year.
- It is assumed that the heat capacity of the zone is time-invariant and is calculated by the heat capacity of the air in the zone multiplied by a factor of 3 to account for other internal mass, such as furniture.
- The temperature set point for the HVAC systems is assumed to be tracked perfectly without time delay or measurement inaccuracies.
- The HVAC distribution system is assumed to be adiabatic and to react without time delay. Thus, an ideal control and operation of the system is assumed.
- No active humidification or dehumidification systems are considered in the mechanical ventilation system. Thus, the latent heating and cooling energy demand is not considered.

4.2 Case Study: Modern Office Space

Using the approach described above, a case study with a speculative office building is carried out. In this case study, a typical office space is modeled, based on literature and expert interviews. The aim is to generate results to evaluate the presented approach and draw conclusions for an office space design for flexibility, presented in chapter 5.

In the following sections, the disturbances, the constant and the flexible design parameter of the office space are described in detail, resulting in the office space design configurations and the setup of the thermal building model.

4.2.1 Weather Data

In this case study, the weather data from the Meteonorm database [84], which is included in TRNSYS 18, is used. The weather station is located in Stuttgart, Germany (N 48.833°, E 9.2°, 318 m a.s.l.). Meteonorm uses measurements from several years in order to calculate a representative dataset for the weather data. In the case of Stuttgart, the outdoor air temperature and the global solar radiation are calculated with data from 2000–2009 and 1996–2015, respectively.

In Figure 14, the monthly mean global solar radiation and ambient temperature for a representative year in Stuttgart are shown. Figure 15 presents the hourly values for the absolute humidity and the ambient temperature. The weather in Stuttgart is typical for a location in the temperate climate zone: The ambient temperature and global solar radiation vary strongly over the year. The weather data indicates a hot season (summer) between June and September, marked in red, and a cold season (winter) between November and March, marked in blue in Figure 14 and Figure 15.

The ambient temperature varies in the course of the year from -13 °C in winter to 32 °C in summer with an annual mean ambient temperature of 9 °C. Therefore, heating is required in winter and cooling in summer. Even when a high temperature occur during the day in summer, night cooling with natural ventilation can be used, because the temperature drops during nighttime. The absolute humidity and the global solar radiation reach their highest values in summer. However, surface cooling systems can be installed almost without causing any dew point problems, as long as the supply temperature of the cooling medium is kept above a certain limit.

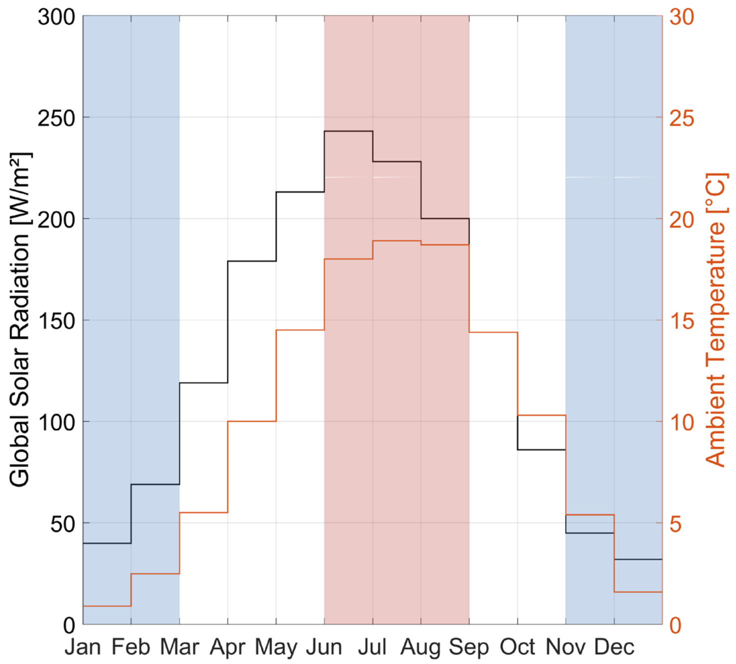


Figure 14. Monthly weather data for Stuttgart

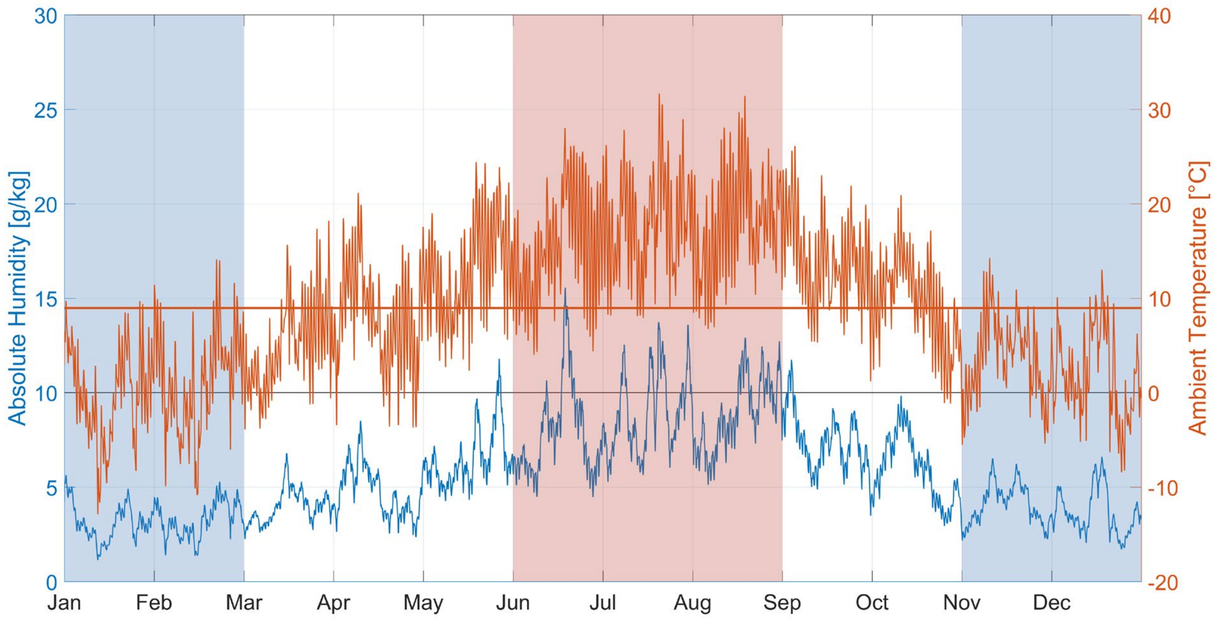


Figure 15. Ambient temperature and absolute humidity for the location Stuttgart, Germany

4.2.2 Building Model

In the following section, the building model, which is based on a typical office building in Stuttgart is described. Here, the constant design parameters, including the building geometry with the grid dimensions and the construction parameters are defined. Afterwards, all internal gains and their related schedules, which are considered as disturbances in the thermal building simulation are presented.

Building Geometry

As shown in Figure 16, the building has three stories and a regular structural and façade grid. Windows are installed on all façades of the building. The building has a rectangular shape, which is typical for an office building and can be categorized in a ribbon shape, triple-loaded building or a point-block building, both with vertical circulation areas in the middle of the floor plan, as illustrated in Figure 17. A more detailed description of the office building typology can be found in section 2.1.2.

Based on this typical structural design, office buildings are designed for a flexible use of space [7]. Figure 18 shows one possible space layout design and furniture option of the office space. In this case, the planning, structural and façade grids are identical and form a square 7.2 m in length and 7.2 m in width. Only the fit-out grid is slightly different in the space layout design option, shown in Figure 18. For simplification, in the thermal building model all grids are identical.

In this case study, only the middle floor of the office building is selected for simulation. The geometry of the resulting thermal building model is illustrated in Figure 19. The floor plan faces north and has a total length of 28.8 m, a width of 21.6 m and height of 3 m, composed of the previously described grid elements. Each grid element forms one airnode in the thermal building model, illustrated in Figure 19.

Figure 16. Cross section (left) and view of the façade (right) (based on [85])

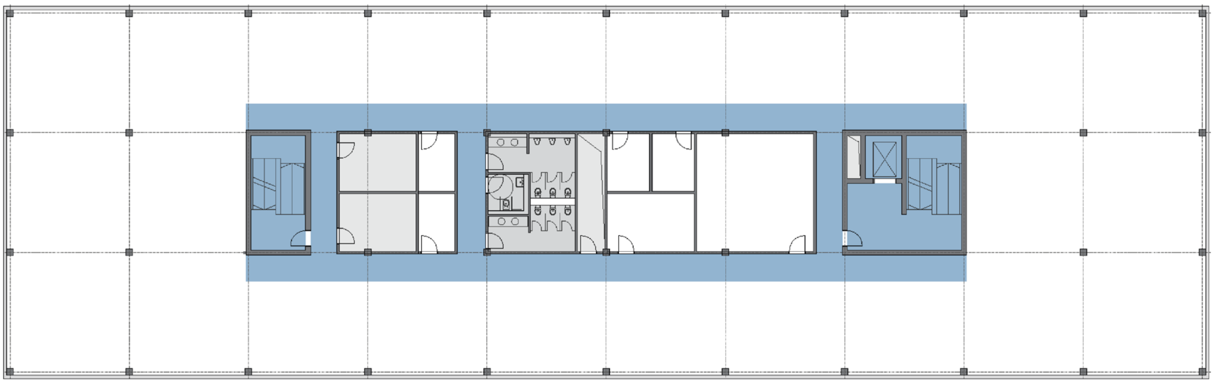


Figure 17. Floor plan with planning grid (based on [85])

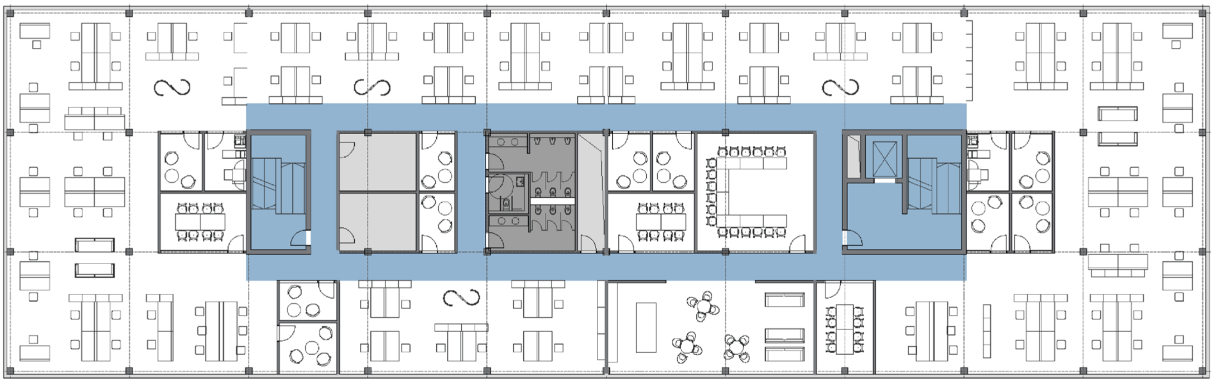


Figure 18. Floor plan with possible space layout design and furniture (based on [85])

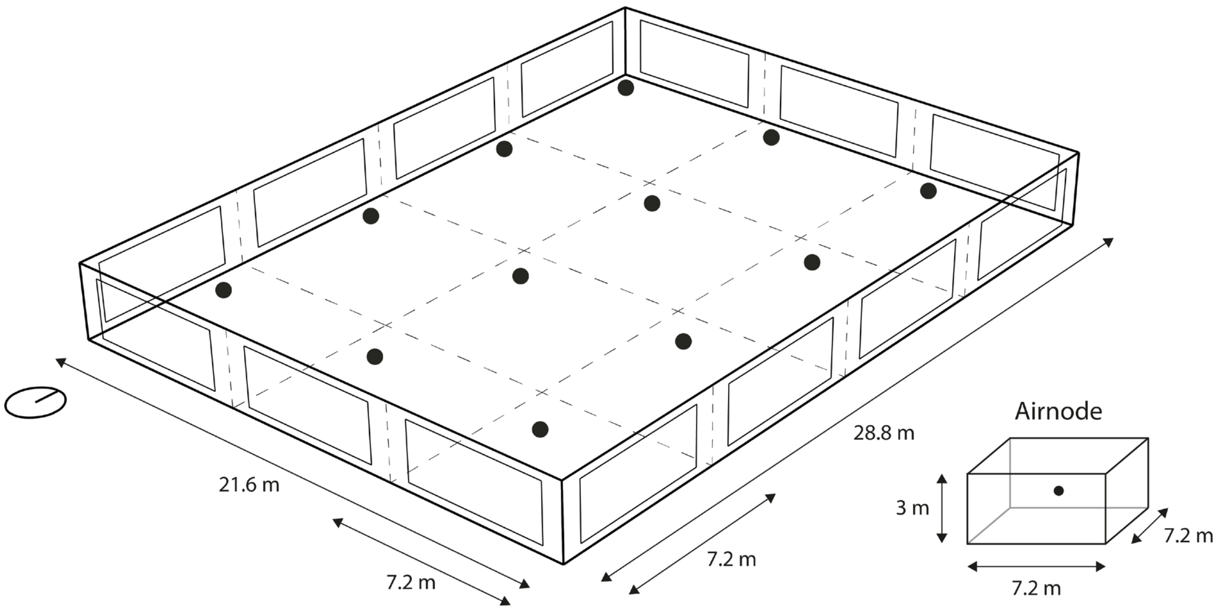


Figure 19. Geometry of the thermal building model and airnode dimensions

Shading

The building model has windows on all façades with a window-to-wall ratio of 0.6 and an automatically operated external shading device with a shading fraction of 75 %. The shading is controlled by an hysteresis, which activates the shading when the solar radiation on the façade exceeds 200 W/m^2 [86] and deactivates it when the radiation falls below 150 W/m^2.

Moreover, additional shading options and control strategies were tested with this model. The results are documented in Appendix A.

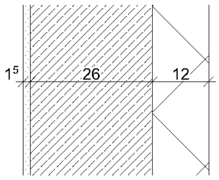
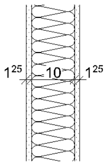
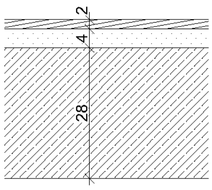
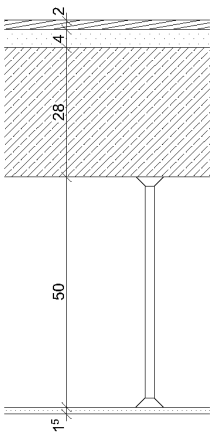
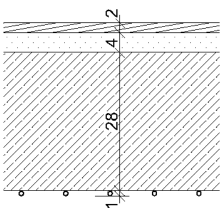
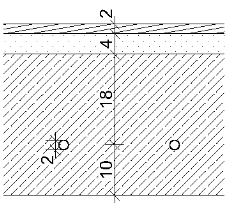
Construction Parameters

For all office space design configurations, the construction of external walls, internal walls, floors and windows is identical. Moreover, the basic construction of the ceiling is the same for all office space design configurations. However, depending on the installed HVAC system, the ceiling needs to be slightly adopted. If a mechanical ventilation system is installed, a suspended ceiling to create space for the air ducts is necessary. If a radiant ceiling is installed, only the pipes are mounted to the ceiling. If a TABS system is installed, the pipes need to be integrated into the concrete layer.

With regard to the thermal quality of the building, the standard values of the German EnEV 2014 [87], which are applicable for non-residential buildings, are fulfilled.

The construction parameters are described in Table 7.

Table 7. Construction parameters

Construction		Components	Thickness	U-Value
External wall		Gypsum Concrete Insulation	1.5 cm 26 cm 12 cm	0.264 $\frac{W}{m^2 \cdot K}$
Internal wall		Gypsum Insulation Gypsum	1.25 cm 10 cm 1.25 cm	0.318 $\frac{W}{m^2 \cdot K}$
Internal floor		Wood Acoustic insulation Concrete	2 cm 4 cm 28 cm	0.743 $\frac{W}{m^2 \cdot K}$
Internal ceiling with MV		Gypsum Air gap Concrete Acoustic insulation Wood	1.5 cm 50 cm 28 cm 4 cm 2 cm	0.493 $\frac{W}{m^2 \cdot K}$
Internal ceiling with RC		Concrete Acoustic insulation Wood	28 cm 4 cm 2 cm	0.511 $\frac{W}{m^2 \cdot K}$
Internal ceiling with TABS		Concrete Acoustic insulation Wood	28 cm 4 cm 2 cm	0.743 $\frac{W}{m^2 \cdot K}$
Window		Triple glazing with aluminum frame Solar heat gain coefficient: 0.5 Solar transmittance: 0.71		0.837 $\frac{W}{m^2 \cdot K}$

4.2.3 Internal Gains and Schedules

The internal gains and their related schedules, which describe their occurrence over time, are defined individually for each airnode. A distinction is made between airnodes, which are located in the meeting room and airnode, which are located in the open-plan office. In general, the internal gains can be generated by people, equipment and lighting. A summary of all internal gains are listed in Table 8.

For the open-plan office, it is assumed that each person is equipped with one laptop and two screens. Moreover, one printer for the complete floor is assumed and the lighting is turned off during midday. Figure 20 illustrates the schedules of the internal gains, including people, equipment and lighting, and the number of occupants in the entire open-plan office.

For the meeting room, it is assumed that each person brings one laptop to the meeting. Moreover, one projector is assumed in the meeting room and the lighting is turned off during absence. Figure 21 illustrates the schedules of the internal gains, including people, equipment and lighting, and the number of occupants in the meeting room.

In order to define the internal gains and schedules for the simulation study presented in this work, an extensive comparison between different applicable standards has been done. The results are presented in Appendix B.

Table 8. Internal gains

Parameters		Open-plan office	Meeting room	Reference
People	Sensible heat gain	70 W	70 W	[23]
	Latent heat gain	45 W	45 W	[23]
	Area per person	10 m^2	3 m^2	[88]
Equipment	Equipment per person	103 W (1 Laptop + 2 Screens)	53 W (1 Laptop)	[23]
	Other equipment in room	1.5 $\frac{W}{m^2}$ (1 Printer)	6 $\frac{W}{m^2}$ (1 Projector)	[23]
Lighting	Light power	10.6 $\frac{W}{m^2}$	13.3 $\frac{W}{m^2}$	[23]

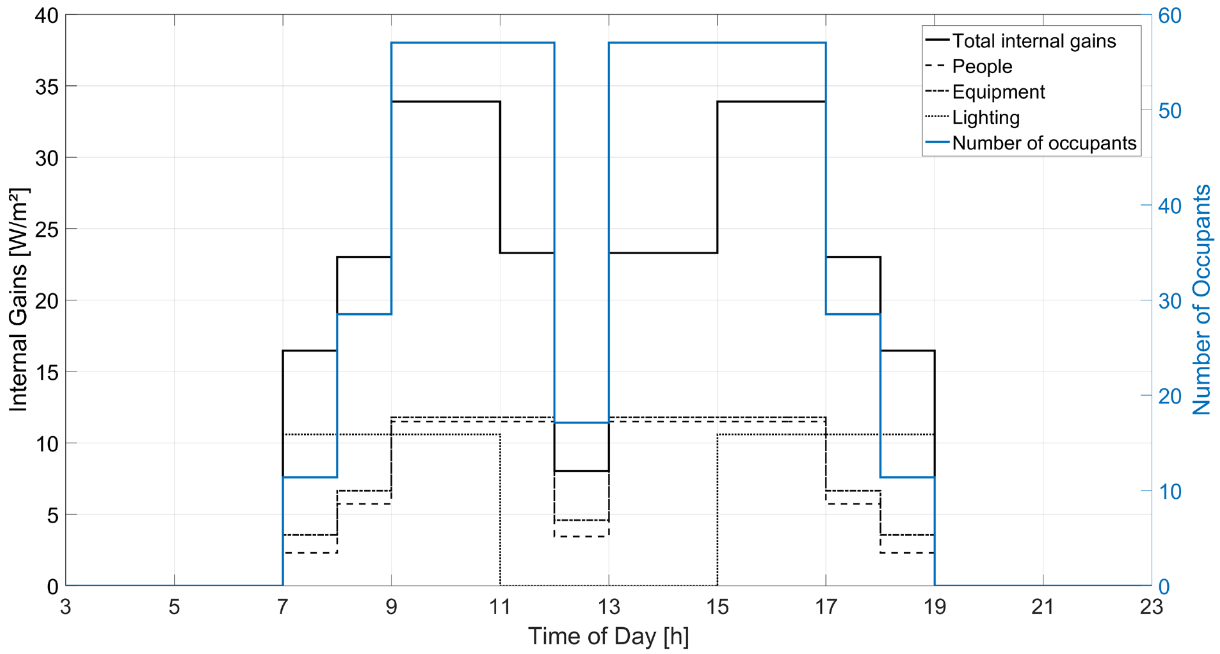


Figure 20. Internal gains and schedules for the open-plan office

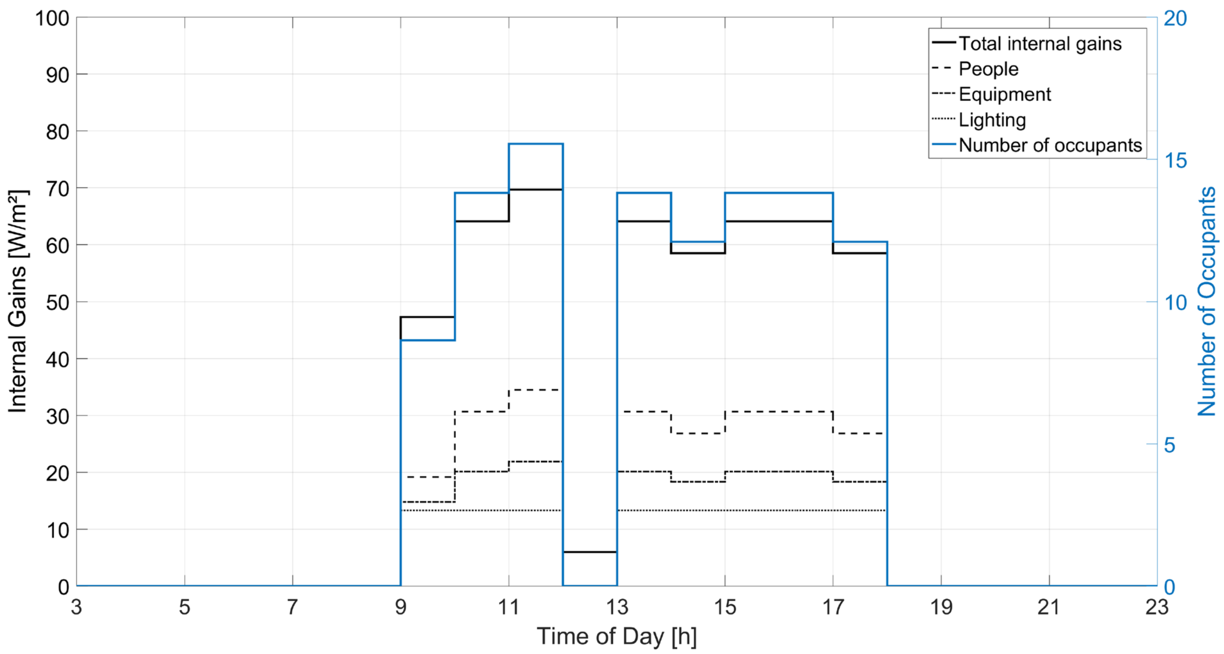


Figure 21. Internal gains and schedules for the meeting room

4.2.4 Space Layout Design

In the presented approach, the space layout design is defined as *flexible* design parameter and thus can be changed between the different office space design configurations. In the following, all space layout design variants, which are applied in this case study are presented.

As illustrated in Figure 22 (left side), the floor plan is composed of 12 airnodes ("A1" to "A12") of the same size, which align with the predefined grid. One airnode in the thermal building model is used as a meeting room and is separated with an interior drywalls of a full ceiling height. The rest of the office space is used as modern open-plan office without interior drywalls and consist of 11 airnodes. In order to model the air exchange in the open-plan office, the airnodes are coupled with a bidirectional airflow of 0.05 m/s [89, 90].

In the following, the airnodes A1, A4, A9 and A12 are referred to as "corner areas", the airnodes A6 and A7 are referred to as "core areas" and all other airnodes are referred to as "perimeter areas". A detailed visualization of these areas can be found in section 5.3 (Figure 54).

In order to model the flexibility of the office space layout, 12 different space layout designs are generated by placing the meeting room at the 12 possible locations on the floor plan, shown in Figure 22 (right side). These positions align with the façade grid, hereinafter referred to as space layout variants number 1 to 12.

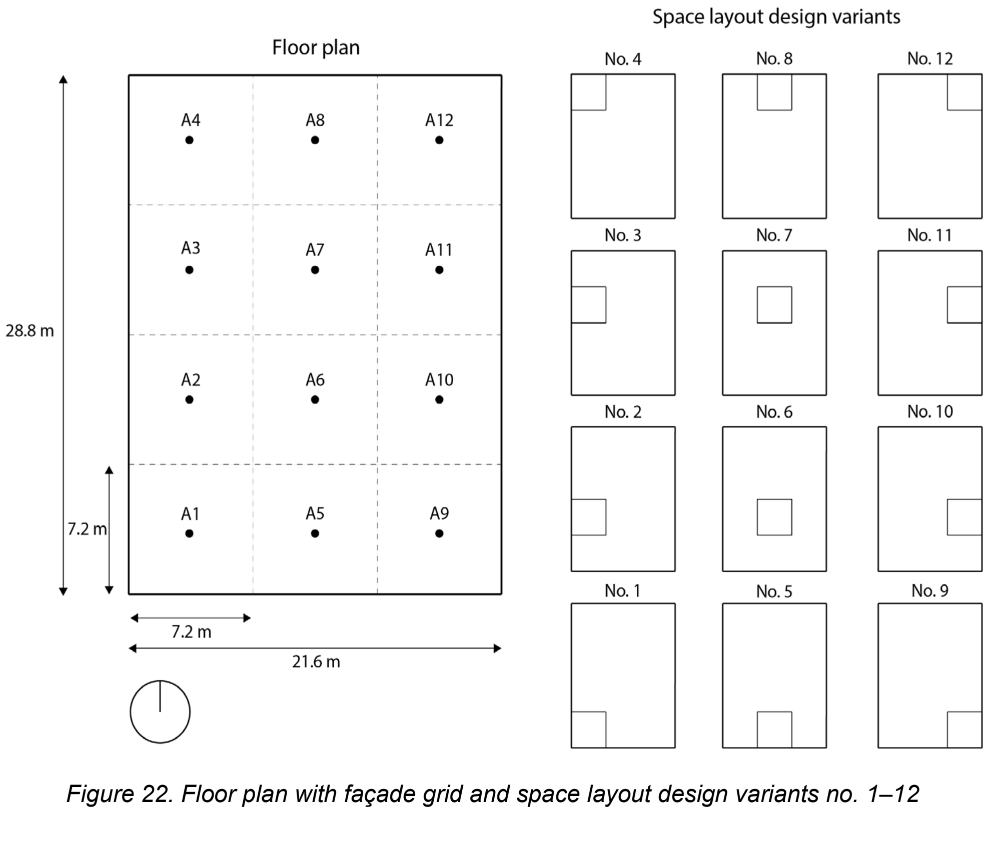


Figure 22. Floor plan with façade grid and space layout design variants no. 1–12

4.2.5 Office Space Design Configurations

In the presented approach, a complete *office space design configuration* is a unique constellation of flexible design parameters, such as illustrated in Figure 12.3. This includes the selection of one space layout design, one HVAC system configuration, one control zoning strategy and the controlled variable. The office space design configuration together with the *constant* design parameters result in the parametric building model, which can be used to carry out the thermal building simulation.

In the following, the flexible design parameters, which are used in this case study to build the office space design configurations, are summarized.

Flexible Design Parameters

As mentioned before, the flexible design parameters are the space layout design and the HVAC system design, including HVAC system configuration, control zoning strategy and the controlled variable. The HVAC system design is described in detail in the next section.

For the space layout design, 12 options are available, for which a meeting room can be placed in 12 different locations according to the predefined grid:

(1) – (12) Space layout designs no. 1–12

For the HVAC system configuration, three options are available:

(1) Only mechanical ventilation (MV)

(2) Radiant ceiling with a basic mechanical ventilation (RC)

(3) TABS with a basic mechanical ventilation (TABS)

For the control zoning strategy, four options are available:

(1) Fine-grained zoning

(2) Core/perimeter zoning

(3) North/south zoning

(4) Room-based zoning

For the controlled variable, two options are available:

(1) Control according to the operative temperature in the control zone

(2) Control according to the air temperature in the control zone

Moreover, simulations with an ideal heating and cooling system (IHC) are carried out to investigate additional aspects of the building design, without considering the limitations and the thermal inertia of a specific HVAC system. The configurations with an IHC do not represent a realistic HVAC system configuration; however, they are necessary for a better understanding of the model's behavior.

Thermal Building Simulation

If all office space design configurations that have been investigated in this case study are considered, the total number of building models generated is 360.

This total number consists of 228 year-round simulations generated using all flexible design parameters mentioned above. In the simulations, each of the 12 airnodes is used to calculate the energy balance of the space it is representing and generates a total dataset of 8760 hourly values for the temperature and energy demand in the airnode. The results are presented in sections 5.2–5.3.

Moreover, an additional number of 132 year-round simulations with an IHC are generated to evaluate the influence of the control zoning strategy and of different shading options on the results. The corresponding results for the control zoning strategy are presented in section 5.2.5 and the results for the shading study are presented in Appendix A.

4.3 HVAC System Design

The presented approach offers the possibility to compare different HVAC systems designs, including the HVAC system configuration, the control zoning strategy and the controlled variable. The HVAC system configuration and the number and position of control zones can be adjusted individually using the parametric building model, and thus are considered as *flexible* design parameters. Using this approach, an evaluation of each HVAC system and control zoning strategy in terms of thermal comfort, energy efficiency and sensitivity to changes in the space layout design can be done. Finding robust solutions for the configuration and control strategy of each HVAC system can support design decisions during the planning or interior renovation phase. In particular, the thermal comfort can be evaluated on a detailed level within the open-plan office to suggest HVAC zoning strategies for each configuration.

In the following sections, the HVAC system configurations, the control zoning strategies and the controlled variables, which are investigated in the case study, are described in detail. Each HVAC system design is defined in accordance with common standards for office buildings and to provide comfortable indoor climate conditions.

4.3.1 HVAC System Control

Control Zoning Strategy

In order to define a control strategy, the first step is to define the spaces in the building whose indoor climate should be individually controlled by the HVAC system. These spaces are known as “control zones”, as described in section 2.3.1. In order to obtain representative results, it is necessary to consider various sizes and numbers of control zones when investigating different HVAC system configurations.

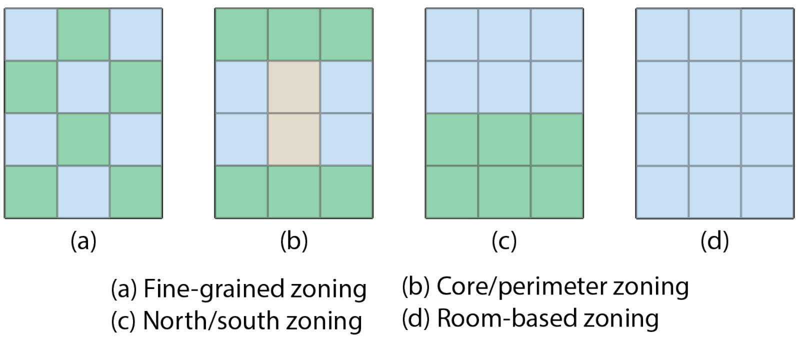


Figure 23. Control zoning strategies

In this case study, four different control zoning strategies for the open-plan office are evaluated. They are illustrated in Figure 23a-d with a decreasing number of control zones from fine-grained zoning, core/perimeter zoning, north/south zoning to room-based zoning. Moreover, the meeting room, which is positioned according to the previously defined space layout variants, is always assumed to have a separately controlled zone.

When *fine-grained* zoning (Figure 23a) is applied, the HVAC system can control the indoor climate individually at the airnode level. This leads to high flexibility in adapting to local heating and cooling loads. The sensor for determining the temperature of the controlled zone is placed in every airnode. In contrast when *room-based* zoning (Figure 23d) is applied, each *room* temperature is controlled individually, including all airnodes within that room. In this study, two rooms are distinguished: a meeting room with one airnode and an open-plan office with 11 airnodes.

Depending on the installed HVAC system, different control zoning strategies and sensor placements can be realized. To achieve this, a specific control strategy is developed for each system in order to implement the desired control zoning in the simulation model.

Controlled Variables and Set Points

After defining the control zones, the controlled variable is defined and the sensor to measure this variable is placed within the control zone. The most commonly used indoor climate variable to control HVAC systems is the air temperature. However, as mentioned in [71]: “[…] people’s thermal comfort responds to operative temperature more directly than air temperature”. This is why for the HVAC system variants in this case study, the room temperature is controlled according to the operative temperature set points defined in the national appendix of DIN EN 15251 [26]. These set points describe a comfortable operative room temperature (T_{op}) depending on the ambient temperature (T_{amb}) according to Equation (4-1)–(4-3). Moreover, a dead band of $\pm$2 K around this temperature set point curve is applied. This method is defined as adaptive approach to evaluate thermal comfort, described in section 2.2.3.

$$T_{\mathrm{op}} = 22 \qquad (T_{\mathrm{amb}} \leq 16\ °\mathrm{C}) \tag{4-1}$$

$$T_{\mathrm{op}} = 18 + 0.25 \cdot T_{\mathrm{amb}} \qquad (16\ °\mathrm{C} < T_{\mathrm{amb}} < 32\ °\mathrm{C}) \tag{4-2}$$

$$T_{\mathrm{op}} = 26 \qquad (T_{\mathrm{amb}} \geq 32\ °\mathrm{C}) \tag{4-3}$$

As illustrated in Figure 24, the heating set point, which defines when the HVAC system is in heating mode, is equal to T_{op} at the lower limit of the dead band. The cooling set point, which defines when the HVAC system is in cooling mode, is equal to T_{op} at the upper limit of the dead band. The exact values of the heating and cooling set point depends on the ambient temperature.

In order to evaluate the effect on thermal comfort of ignoring the operative temperature as the controlled variable, a control according to the indoor air temperature (T_{air}) instead of T_{op} is simulated. The set points are defined according to Equation (4-1)–(4-3), too. To find the most suitable solution for each HVAC system, a comparison between the control strategies with T_{air} and T_{op} is made.

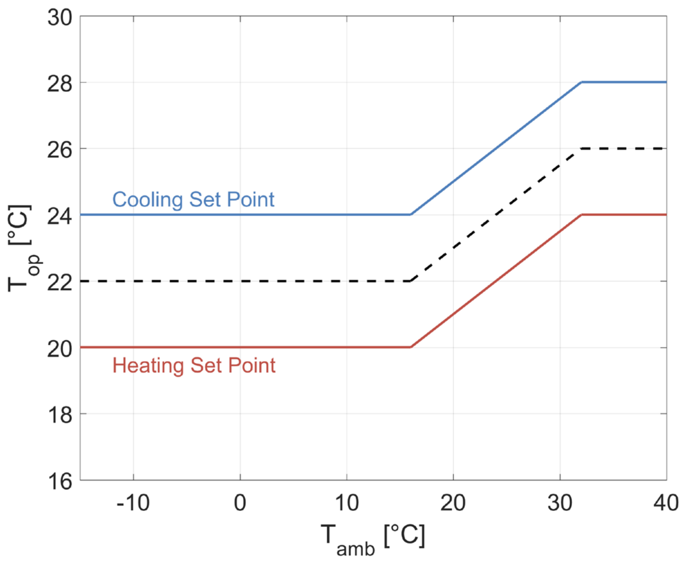


Figure 24. Heating and cooling set points as a function of the ambient (T_{amb}) and operative (T_{op}) temperature

4.3.2 Ideal Heating and Cooling System

Initially, the building model is simulated with an *ideal heating and cooling system* (IHC) with unlimited power supply, as described in section 2.3.3. This method does not consider a realistic HVAC system configuration, but conditions the space in an idealized way. These variants are simulated to analyze only the influence of the control zoning strategy on thermal comfort and energy demand, without considering the inertia and limits of a specific HVAC system. Moreover, a study with different shading options is carried out using the IHC, presented in Appendix A.

The parameters assumed for the simulation setup with an IHC are shown in Table 9.

Table 9. Simulation setup for variants with an ideal heating and cooling system

Parameters	Open-plan office	Meeting room	Reference
Temperature set point	$f(T_{\mathrm{amb}})$, according to Eq. (4-1)–(4-3)	$f(T_{\mathrm{amb}})$, according to Eq. (4-1)–(4-3)	[26]
Controlled variable	T_{op} or T_{air}	T_{op} or T_{air}	
Power limit	Unlimited	Unlimited	
Daily operating hours	5 a.m.–7 p.m.	5 a.m.–7 p.m.	
Air infiltration	$0.1\,\frac{1}{\mathrm{h}}$ in all airnodes	$0.1\,\frac{1}{\mathrm{h}}$ in all airnodes	[86]
Control Strategy	The parallel model is used to calculate the power limit of each time step for the ideal heating and cooling component in the airnodes of the original model. Therefore, all airnodes within the same control zone have the same power limit and thus also power supply.		

Control Zoning Strategy

To model a control zone for an IHC, a novel approach have been developed. In the following, this approach is described for modelling the open-plan office as one control zone, following the *room-based zoning* strategy explained before. For each variant, a *parallel model* is built with the same properties as the original building model. The only difference between the parallel model and the original building model is that the open-plan office in the parallel model consists of one airnode instead of 11 airnodes, illustrated in Figure 25. This is necessary, because the IHC always provides enough heating and cooling power to keep the indoor climate of the airnode in comfortable conditions, as explained in 2.3.3. If the number of airnodes is reduced to one, the IHC would only calculate the heating and cooling power for this one airnode and would ignores the heating and cooling load in the other airnodes. By employing the parallel model, an ideal heating and cooling for one control zone and not one airnode can be enforced.

With the simulation results from this one airnode in the parallel model, the mean heating or cooling power required in each time step for the open-plan office can be calculated. This mean power is then supplied to each airnode of the open-plan office in the original building model. It is noted that this mean power is applied independently of the power these airnodes would require if they were individually controlled with IHC. By applying the steps described previously, a room-based control zoning with IHC can be simulated and thus the limitations in TRNSYS in this respect are overcome. This approach can also be used to model different control zoning strategies by obtaining different thermal zones from the parallel model.

For the control zoning strategies in this case study, the meeting room is always controlled according to the temperature in its airnode and does not use the parallel model approach. It is assumed that the temperature sensor in the meeting room moves with it when it is rearranged according to the previously defined space layout design variants.

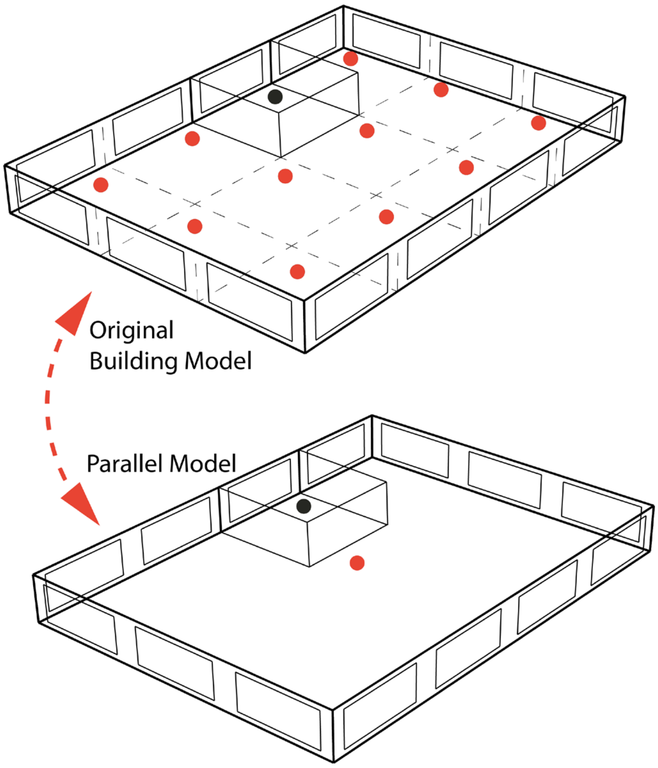


Figure 25. Parallel model approach for a room-based control zoning and the space layout design no. 3

4.3.3 Mechanical Ventilation

Basic Mechanical Ventilation

For each configuration of the simulated HVAC system, the minimum fresh air required according to DIN EN 15251 Table B.3 [26] is provided with a mechanical ventilation (MV) system that operates from 5 a.m. to 7 p.m. with a constant supply temperature of 18 °C and a heat recovery of 80 %. With this system, a minimum air change per hour (ACH) of 1.68 h^{-1} is provided in airnodes located in the open-plan office and a minimum ACH of 3.64 h^{-1} in the meeting room. The fan power is calculated based on the volume flow, with a constant factor of 1300 $W/(m^3 \cdot s^{-1})$, which corresponds to SPF[1] category 4 in [91]. Besides the mechanical ventilation, natural infiltration due to air leakage in the building envelope is assumed to have a constant ACH of 0.1 h^{-1} in all airnodes adjacent to a façade [86].

The parameters assumed for the simulation setup with a basic mechanical ventilation are shown in Table 10.

Table 10. Simulation setup for the variants with a basic mechanical ventilation

Parameters	Open-plan office	Meeting room	Reference
Daily operating hours	5 a.m.–7 p.m.	5 a.m.–7 p.m.	
Constant minimum ACH	$1.68\ \frac{1}{h}$	$3.64\ \frac{1}{h}$	[26]
Supply temperature	18 °C	18 °C	
Heat recovery	80 %	80 %	
Specific fan power	$1300\ \frac{W}{m^3 \cdot s^{-1}} = 0.36\ \frac{W}{m^3 \cdot h^{-1}}$	$1300\ \frac{W}{m^3 \cdot s^{-1}} = 0.36\ \frac{W}{m^3 \cdot h^{-1}}$	SPF 4 [91]
Control Strategy	Each airnode is conditioned with a constant volume flow according to the room usage (open-plan or meeting room).		

[1] SPF: Specific fan power

HVAC System Configuration No. 1: Only Mechanical Ventilation

The first HVAC system configuration uses only a mechanical ventilation (MV) system to condition the office space (Figure 26). For simplification purposes, in the remainder of this work this system is referred to as “MV”. For all variants with this HVAC system configuration, the TRNSYS Type 336 (air handling unit with heat recovery) [42] is used to simulate the system. The method to calculate the heating, cooling and fan power is presented in section 2.3.3.

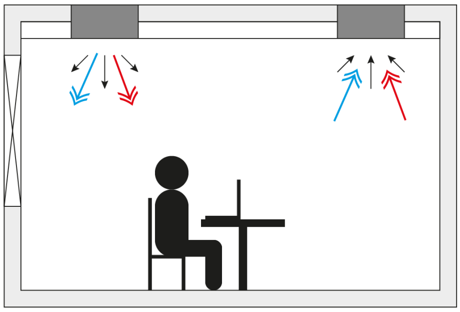


Figure 26. HVAC system configuration no. 1 – only mechanical ventilation

The supply air temperature (T_{sup}) is adjusted according to the operative room temperature (T_{op}) and the ambient temperature (T_{amb}), as illustrated in Figure 27. If T_{op} is above the cooling set point (blue area), T_{sup} is 17 °C. If T_{op} is below the heating set point (red area), T_{sup} is 23 °C. If T_{op} is below the cooling set point and above the heating set point (yellow area), T_{sup} is always 18 °C for the meeting room (Figure 27, right side). For the open-plan office (Figure 27, left side), T_{sup} is 20 °C if T_{amb} is below 10 °C and T_{sup} is 18 °C if T_{amb} is above 10 °C.

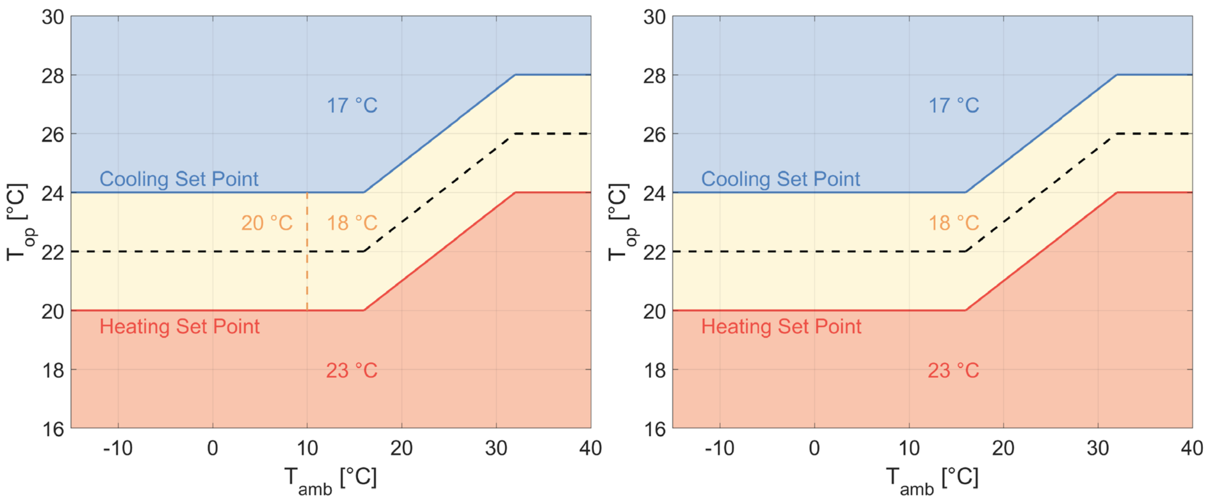


Figure 27. MV supply air temperature for open-plan office (left) and meeting room (right), depending on the operative room temperature (T_{op}) and the ambient temperature (T_{amb})

In addition to the minimal required fresh air, a maximum of 3.33 ACH for the open-plan office and 5.0 ACH for the meeting room [26] can be realized. If the temperature in the room is within the predefined temperature range, described in section 4.3.1, the system operates with the minimum ACH; if not, the system runs with maximum ACH. The MV is also equipped with a heat recovery of 80 % and has additionally the possibility of recirculating the room air, as described in section 2.3.3. However, the amount of the recirculated air is always defined considering the requirements for the minimum ACH with the ambient air.

The parameters assumed for the simulation setup with MV are shown in Table 11.

Control Zoning Strategy

To control the system according to the zoning strategies described in section 4.3.1, it is assumed that the air of all airnodes in one control zone is perfectly mixed in the exhaust air duct, where the temperature is assumed to be measured. The zone is controlled according to the resulting mixed air temperature.

Table 11. Simulation setup for the variants with MV

Parameters	Open-plan office	Meeting room	Reference
Temperature set point	$f(T_{\mathrm{amb}})$, according to Eq. (4-1)–(4-3)	$f(T_{\mathrm{amb}})$, according to Eq. (4-1)–(4-3)	[26]
Controlled variable	T_{op} or T_{air}	T_{op} or T_{air}	
Daily operating hours	5 a.m.–7 p.m.	5 a.m.–7 p.m.	
Minimum ACH	1.68 $\frac{1}{\mathrm{h}}$	3.64 $\frac{1}{\mathrm{h}}$	[26]
Maximum ACH	3.33 $\frac{1}{\mathrm{h}}$	5 $\frac{1}{\mathrm{h}}$	[26]
Supply temperature	Winter 20 °C, summer 18 °C Max. 23 °C, min 17 °C	Winter 18 °C, summer 18 °C Max. 23 °C, min 17 °C	
Heat recovery	80 % + recirculation of room air	80 % + recirculation of room air	
Specific fan power	1300 $\frac{\mathrm{W}}{\mathrm{m^3 \cdot s^{-1}}}$ = 0.36 $\frac{\mathrm{W}}{\mathrm{m^3 \cdot h^{-1}}}$	1300 $\frac{\mathrm{W}}{\mathrm{m^3 \cdot s^{-1}}}$ = 0.36 $\frac{\mathrm{W}}{\mathrm{m^3 \cdot h^{-1}}}$	[91]
Air infiltration	0.1 $\frac{1}{\mathrm{h}}$ in perimeter airnodes	0.1 $\frac{1}{\mathrm{h}}$ in perimeter airnodes	[86]
Control strategy	It is assumed that the air from airnodes within the same control zone is mixed in the exhaust air duct. All airnodes within the control zone are conditioned according to the temperature in the corresponding exhaust air duct.		

4.3.4 Radiant Ceiling

HVAC System Configuration No. 2: Radiant Ceilings with Basic Mechanical Ventilation

The second HVAC system configuration uses *radiant ceilings* (RC), which are suspended from the ceiling to heat and cool the office space, and a basic mechanical ventilation to provide the space with enough fresh air. Due to the central role of radiant ceilings in this configuration, it is referred to as “RC” in the remainder of this work. The RC configuration is illustrated in Figure 28. The method to calculate the heating and cooling power of the radiant ceilings that is used in the thermal building simulation is presented in section 2.3.3.

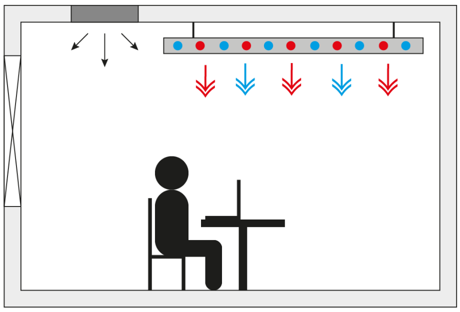


Figure 28. HVAC system configuration no. 2 – radiant ceilings with basic mechanical ventilation

The RC used in this case study cover 58 % of the ceiling area in the office space. With a mass flow of 37 kg/(h·m^2) [92] and a fluid temperature of the supply water of 18 °C for cooling and 35 °C for heating [93], a maximum cooling power of 86 W/m^2 [92] and maximum heating power of 60 W/m^2 [14] can be obtained. Each RC module has a size of 9.94 m^2, a pipe length of 120 m and a pipe diameter of 0.01 m.

The parameters assumed for the simulation setup with radiant ceilings are shown in Table 12. A list of all construction parameters of the radiant ceiling can be found in Appendix C.

Control Zoning Strategy

Equipped with a 4-way valve, the RC modules are able to heat and cool, as necessary, without the necessity for winter and summer-specific operation modes. The mass flow and supply temperature in the pipes are controlled according to the measured temperature in the room using a differential controller (TYPE 2 from TRNSYS 18 [44]). To minimize the number of sensors required in the room, different zoning strategies are tested. Each control zone has one sensor, illustrated in Figure 29, in which the points represent the placement of the sensors in the open-plan office. The measurements from these sensors are employed when the temperature is controlled for the airnodes in the correspondingly colored area.

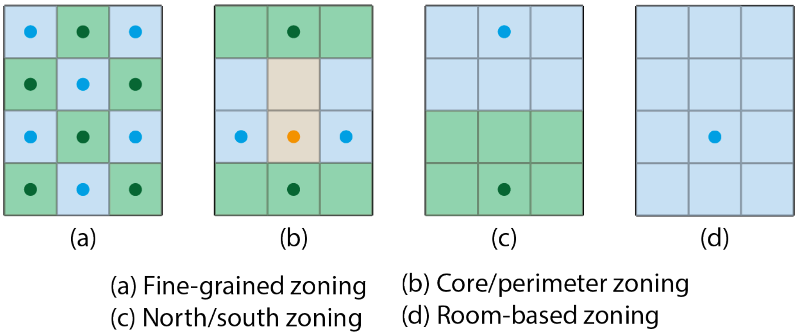


Figure 29. Radiant ceiling control zoning strategies and sensor placement

For example, to realize *room-based zoning* (Figure 29d) all airnodes in the open office zone are controlled according to the temperature in airnode A6, except for space layout variant no. 6, in which the sensor is placed in airnode A7, because the meeting room is placed in airnode A6. The sensor placement is applied analogously in all zoning strategies.

Table 12. Simulation setup for the variants with RC

Parameters	Open-plan office and meeting room	Reference
Temperature set point	$f(T_{\text{amb}})$, according to Eq. (4-1)–(4-3)	[26]
Controlled variable	T_{op} or T_{air}	
Daily operating hours	5 a.m.–7 p.m.	
Percentage of total ceiling area	58 %	[92]
Specific mass flow	37 $\frac{kg}{h \cdot m^2}$	[92]
Cooling power	86 $\frac{\text{W}}{\text{m}^2}$	[92]
Heating power	60 $\frac{\text{W}}{\text{m}^2}$	[14]
Fluid supply temperature	Heating 35 °C, cooling 18 °C	[93]
Air infiltration	0.1 $\frac{1}{\text{h}}$ in perimeter airnodes	[86]
Control strategy	It is assumed that the sensor to measure the temperature in a control zone is placed in only one airnode of this control zone. All airnodes within the control zone are conditioned according to this measured value.	

4.3.5 TABS

HVAC System Configuration No. 3: TABS with Basic Mechanical Ventilation

The third HVAC system configuration uses a *thermally-active building system* (TABS) to heat and cool the office space, thus being referred to as "TABS" in the remainder of this work. Additionally, the configuration includes a basic mechanical ventilation to provide the space with enough fresh air. The TABS configuration is illustrated in Figure 30.

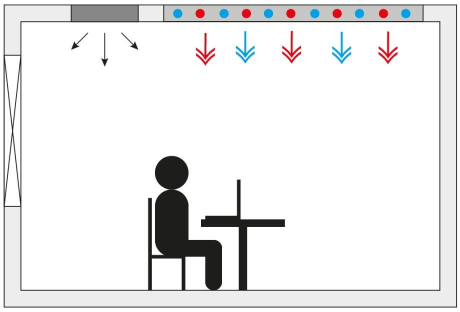


Figure 30. HVAC system configuration no.3 – TABS with basic mechanical ventilation

The pipes for the TABS are embedded in the center of the concrete construction slab and the pipes cover 80 % of the ceiling area, enhancing the thermal storage capacity of the building. In this case study, the TABS are operated 24 hours per day [94], with a constant mass flow of 19 kg/(h·m^2) and varying fluid supply temperature, resulting in an maximum cooling power of 50 W/m^2 and heating power of 40 W/m^2 [14]. The method to calculate the heat transfer between the TABS and the room air, which is used in the thermal building simulation, is presented in section 2.3.3.

The parameters assumed for the simulation setup with TABS are shown in Table 13. A list of all construction parameters of the TABS can be found in Appendix C.

Table 13. Simulation setup for variants with TABS

Parameters	Open-plan office and meeting room	Reference
Daily operating hours	24 h	[94]
Percentage of total ceiling area	80 %	[94]
Specific mass flow	Constant with 19 $\frac{\mathrm{kg}}{\mathrm{h \cdot m^2}}$	
Cooling power	50 $\frac{\mathrm{W}}{\mathrm{m^2}}$	[14]
Heating power	40 $\frac{\mathrm{W}}{\mathrm{m^2}}$	[14]
Fluid supply temperature	$f(T_{\mathrm{amb,24h}})$, according to Eq. (4-4)–(4-6)	
Air infiltration	0.1 $\frac{1}{\mathrm{h}}$ in perimeter airnodes	[86]
Control strategy	Different heating and cooling curves are used to calculate the supply temperature for each airnode. Airnodes that are conditioned according to the same heating and cooling curves are within the same control zone.	

Control Zoning Strategy

Heating and cooling curves (HC) are used to calculate the supply temperature based on the mean ambient temperature over the past 24 hours ($T_{\mathrm{amb,24h}}$). Using HC to define the supply temperature set point of the TABS is common practice [94]. Consequently, the TABS control strategy does not receive feedback from the room but is regulated only by the outside weather conditions. To implement different zoning strategies within the office space, three different HC are used, illustrated in Figure 31. The supply temperature for the open-plan office ($T_{\mathrm{sup,office}}$) is calculated according to Equation (4-4), for the meeting room ($T_{\mathrm{sup,MR}}$) according to Equation (4-5) and for the meeting room in space layout variants no. 6 and no. 7 ($T_{\mathrm{sup,MR,core}}$) when it is placed in the middle airnodes according to Equation (4-6).

$$T_{\mathrm{sup,office}} = -0.1 \cdot T_{\mathrm{amb,24h}} + 23 \tag{4-4}$$

$$T_{\mathrm{sup,MR}} = -0.175 \cdot T_{\mathrm{amb,24h}} + 21.25 \tag{4-5}$$

$$T_{\mathrm{sup,MR,core}} = 19 \tag{4-6}$$

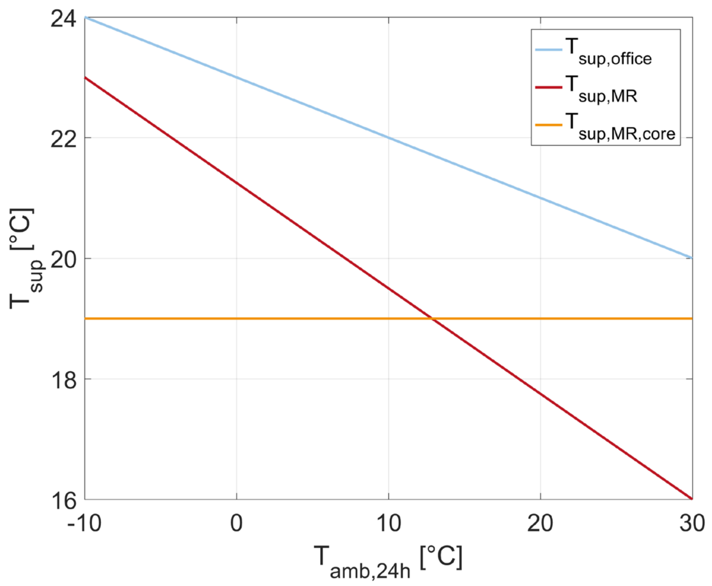


Figure 31. Heating and cooling curves for TABS

Applying the above-mentioned HC results in the zoning strategies, which are illustrated in Figure 32. Airnodes marked in blue represent the open-plan office space with a supply temperature according to Equation (4-4). Airnodes marked in red represent the meeting room in space layout design variant no. 1 with a supply temperature according to Equation (4-5) and those marked in orange represent the meeting room in space layout variants no. 6 and no. 7, with a supply temperature according to Equation (4-6).

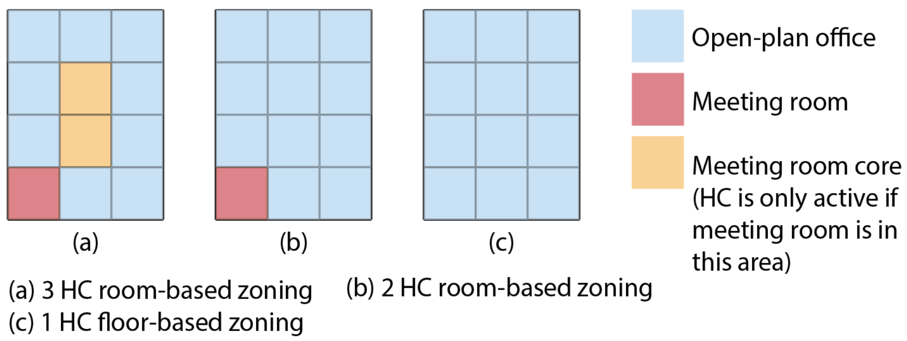


Figure 32. Control zoning strategies for TABS

5 Research Results and Discussion

In this chapter, the research results are presented and discussed. First of all, the criteria to evaluate the results of the case study are presented. Then, the influence of each *flexible* design parameter on thermal comfort, energy demand and robustness of the office space are investigated in detail. These are the HVAC system design, including its configuration, control zoning strategy and the controlled variable, and the space layout design.

The HVAC system design evaluation first provides an overview of the results for all HVAC system configurations, with a focus on comparing the different HVAC system design. Then, the simulation results for each HVAC system configuration is discussed in detail, with a particular focus on the influence of the control zoning strategy and the space layout design, to evaluate the system's flexibility.

For the evaluation of the space layout design, the influence on thermal comfort and energy demand is described for each HVAC system design. Moreover, a recommendation is given for each HVAC system design regarding the flexibility of the space layout design.

After the presentation of the results, the limitations in the applicability of this approach are also discussed. It is noted that a selection of these results was published in [82].

5.1 Evaluation Criteria

To investigate thermal comfort, energy demand and flexibility, the office space is assessed on a detailed level. Accordingly, each airnode in the thermal building model is evaluated over a whole year with changing space layout designs, HVAC system configurations, control zoning strategies and controlled variables, summarized as flexible design parameters. In the following, the evaluation criteria for thermal comfort, energy demand and robustness is described.

5.1.1 Thermal Comfort

The thermal comfort is evaluated based on the calculated thermal comfort violations (CV) defined in DIN EN 15251 [26]. The CV are calculated according to Equation (5-1)–(5-3), thereby distinguishing between overheating hours (CV_{hot}) and too cold conditions (CV_{cold}) in the airnodes. Overheating occur if the operative temperature in the airnode (T_{op}) is larger than the upper comfort limit ($T_{\mathrm{op,upper}}$) and too cold conditions occur if it is smaller than the lower comfort limit ($T_{\mathrm{op,lower}}$). These comfort violations are calculated with the magnitude of the violation, the time (Δt) during which the comfort violation occur and the number of occurrences (m) during the analyzed period.

$$CV_{\mathrm{hot}} = \sum_{k=1}^{m} |T_{\mathrm{op}} - T_{\mathrm{op,upper}}|_k \cdot \Delta t \quad (if\ T_{\mathrm{op}} > T_{\mathrm{op,upper}}) \tag{5-1}$$

$$CV_{\mathrm{cold}} = \sum_{\mathrm{k}=1}^{m} \left|T_{\mathrm{op}} - T_{\mathrm{op,lower}}\right|_k \cdot \Delta t \quad (if\ T_{\mathrm{op}} < T_{\mathrm{op,lower}}) \tag{5-2}$$

$$CV = CV_{\mathrm{hot}} + CV_{\mathrm{cold}} \tag{5-3}$$

The limits for CV in the open-plan office ($CV_{\mathrm{limit,office}}$) and the meeting room ($CV_{\mathrm{limit,MR}}$) are also calculated according to DIN EN 15251 [26]. Here, in a building of category II, an equivalent of 1 % of the occupied time with a deviation of 2 K is allowed. In this case, the open-plan office is occupied for 12 hours per day and the meeting room for 8 hours per day, while both are not occupied at weekends. Thus, the CV limits are calculated as follows:

$$CV_{\mathrm{limit,office}} = \frac{1}{100} \cdot \left(12\,\frac{\mathrm{h}}{\mathrm{d}} \cdot 261\,\frac{\mathrm{d}}{\mathrm{a}}\right) \cdot 2\ \mathrm{K} = 63\ \mathrm{Kh/a} \tag{5-4}$$

$$CV_{\mathrm{limit,MR}} = \frac{1}{100} \cdot \left(8\,\frac{\mathrm{h}}{\mathrm{d}} \cdot 261\,\frac{\mathrm{d}}{\mathrm{a}}\right) \cdot 2\ \mathrm{K} = 42\ \mathrm{Kh/a} \tag{5-5}$$

This dissertation focuses only on CV and does not question the applicability of standards, being aware that thermal comfort boundaries are highly subjective and vary on a personal level.

5.1.2 Energy Demand

The energy demand required to condition the office space is calculated for each airnode and compared between all simulated variants. This analysis includes the energy demand for heating (E_{heat}) and cooling (E_{cool}) the space, as well as for the electricity for pumps and fans (E_{elec}). For the calculation of the energy use intensity (EUI) it is assumed that the energy is generated by a heat pump with a seasonal coefficient of performance ($SCOP$) of 4.0 for heating and a seasonal energy efficiency ratio ($SEER$) of 5.6 for cooling according to the European Ecodesign Directive [95].

The EUI is calculated as follows:

$$EUI = \frac{E_{\mathrm{heat}}}{SCOP} + \frac{E_{\mathrm{cool}}}{SEER} + E_{\mathrm{elec}} \tag{5-6}$$

5.1.3 Robustness to Changes in the Space Layout Design

For an office building with a flexible space layout design, the sensitivity of the thermal comfort and energy demand to changes are particularly interesting. To quantify the robustness for these changing boundary conditions, the standard deviation (σ) is calculated for the energy demand ($EUI, E_{\mathrm{heat}}, E_{\mathrm{cool}}$) and the comfort violations (CV, $CV_{\mathrm{hot}}, CV_{\mathrm{cold}}$) according to Equation (5-7):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} |x_i - \bar{x}|^2} \tag{5-7}$$

with n being the total number of airnodes, i being the airnode index and x being the value of $EUI, E_{\mathrm{heat}}, E_{\mathrm{cool}}, CV$, CV_{hot} and CV_{cold}.

In this dissertation, it is defined that an HVAC system design called “robust” if the standard deviation for all space layout design variants is less than 5 % of the mean value of the corresponding variable. This indicates that the range in which the values lie are small compared to the mean value for all space layout design variants, thus the variations are low. In addition, then the space layout design is called “flexible”.

Furthermore, if both the space layout design and the control zoning strategy of the HVAC system can be changed without a significant influence on thermal comfort and energy demand, the variants are called “fully flexible”.

5.2 Influence of the HVAC System Design

As mentioned before, the HVAC system design in this dissertation consists of the HVAC system configuration, the control zoning strategy and the controlled variable. The HVAC system design is part of the *flexible* design parameters in the building model, illustrated in Figure 33.

In this chapter, the influence of each part of an HVAC system design on thermal comfort, energy demand and robustness are presented. First, an overview of the results for all HVAC system configurations is presented, focusing on the comparison between the HVAC system design. Then, the simulation results for each HVAC system configuration are discussed in detail, with a particular focus on the different control zoning strategies, space layout designs and the overall flexibility of the system.

For simplification, in the following the HVAC system configuration no. 1 (only mechanical ventilation) is referred to as “MV”, configuration no. 2 (radiant ceilings and basic mechanical ventilation) is referred to as “RC” and configuration no. 3 (TABS and basic mechanical ventilation) is referred to as “TABS”. Similarly, “a decreasing number of control zones”, refers to a change in the control zoning strategy towards a coarser zonal resolution, e.g. from a fine-grained zoning with 11 control zones in the open-plan office, to a core/perimeter zoning with five control zones, to a north/south zoning with two control zones, to a room-based zoning with one control zone.

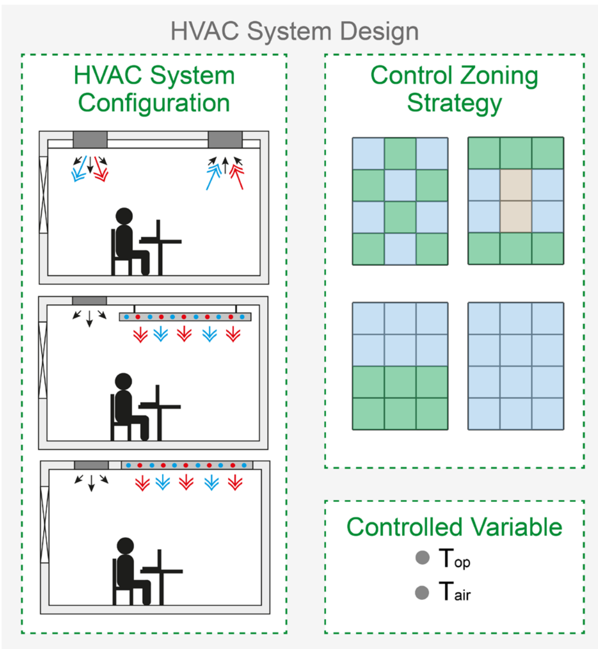


Figure 33. HVAC system design as part of the flexible design parameters

5.2.1 Influence of the HVAC System Configuration

First, an overview of the results for the HVAC system configurations, each of which is described in detail in sections 4.3.3–4.3.5, is presented.

Energy Demand

The monthly energy demand for heating, cooling and electricity for MV, RC and TABS with fine-grained zoning is illustrated in Figure 34. The energy demand is calculated as the mean value for all space layout design variants and airnodes for each month, representing the total energy provided by the electric grid. Comparing the total monthly energy demand for each HVAC system clearly shows that the MV requires the highest energy demand due to the high electricity demand of the fan. The heating and cooling energy demand of the hydronic systems in the RC and TABS configuration are similar. However, in the warm summer months (July and August) and the cold winter months (January, February and December), the energy demand for TABS is slightly higher than for RC. It is noted that for both the RC and TABS variants, an MV is needed to provide the minimum required ACH for fresh air, thus resulting in a non-zero heating energy, cooling energy and electricity demand for MV in these cases.

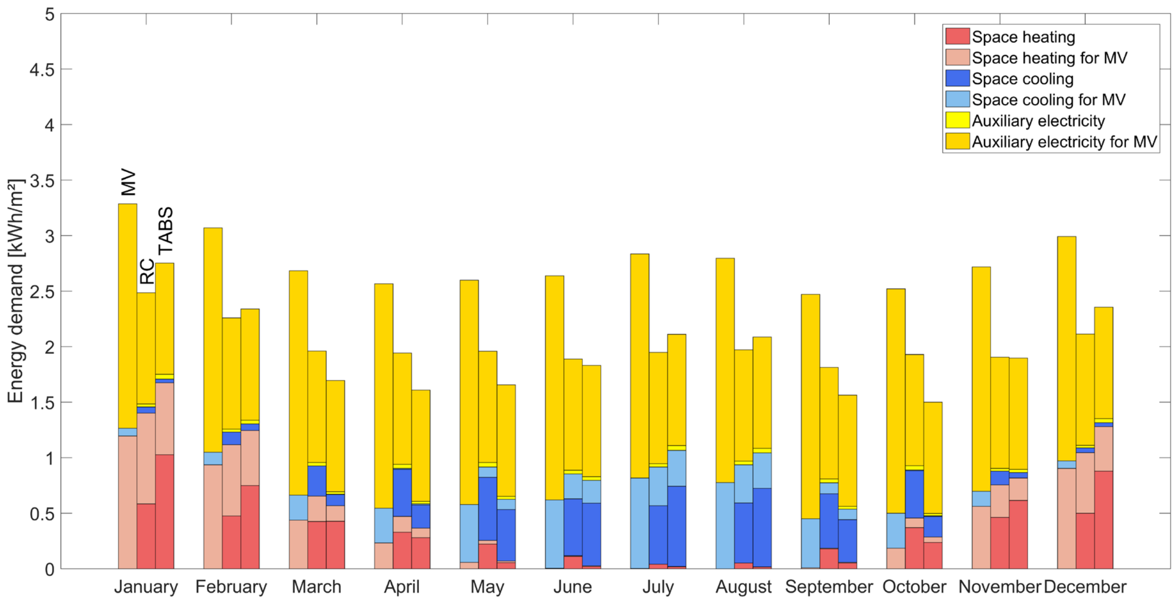


Figure 34. Comparison of monthly energy demand for all HVAC system configurations with fine-grained zoning, each HVAC system configuration (MV, RC, TABS) is represented with one bar per month

Thermal Comfort

Figure 35 compares the CV with the EUI of each airnode in the open-plan office for all simulated HVAC system configurations, control zoning strategies and space layout design variants. Here, each dot represents the results for one airnode in the open-plan office.

For the open-plan office (Figure 35), the MV achieves higher CV and EUI values than most other variants. To avoid high CV using the MV system, it is necessary to adapt the system properly, as described in section 5.2.2. Both RC and TABS remain within the CV limit for the open-plan office but RC shows a higher variance in the EUI. The influence of control zoning on CV and EUI is discussed in the following sections for each HVAC system configuration.

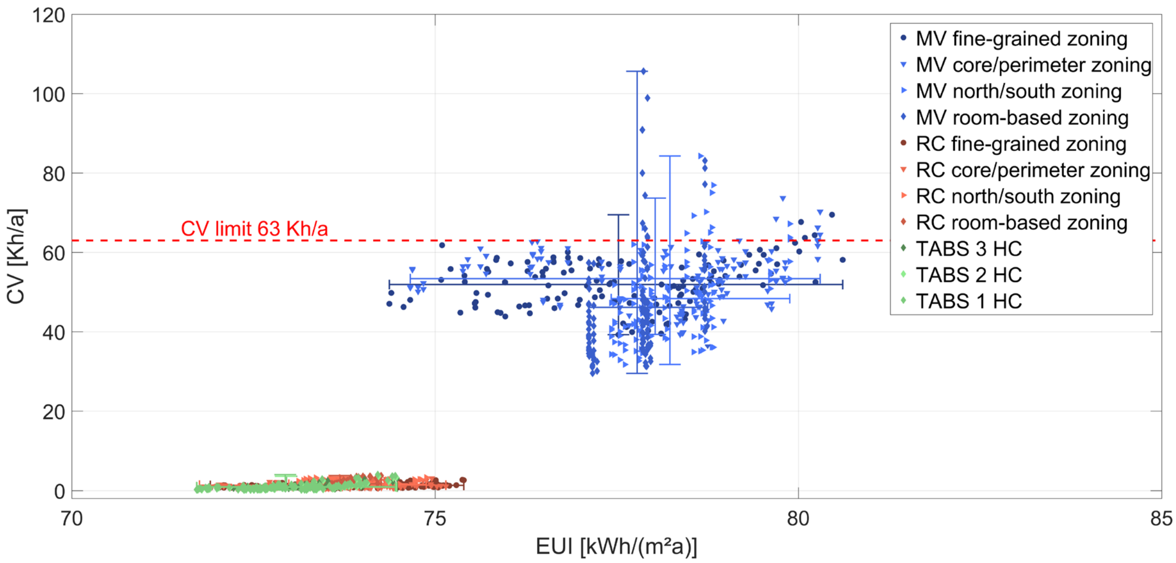


Figure 35. CV and EUI for open-plan office airnodes in all variants

In addition, Figure 36 compares the CV_{hot} with the cooling energy demand (E_{cool}) and Figure 37 compares CV_{cold} with the heating energy demand (E_{heat}). For the variants with MV and TABS, most CV in the open-plan office occur due to overheating (CV_{hot}), whereas for variants with RC, no CV_{hot} in the open-plan office occur, as illustrated in Figure 36.

Moreover, the variants with RC show the largest variations between the cooling energy demand in each airnode of the open-plan office, especailly for variants with a fine-grained zoning. If less control zones are defined, less variations in the cooling energy demand occur. This indicates that the RC is able to react fast and efficiently to overheating in the airnode and can adjust its cooling power respectively. More details on the results for RC are described in section 5.2.3.

In contrast, for variants with TABS the variations in the cooling energy demand are small. This can be explained by the high thermal inertia of the TABS resulting in a low reactivity to variations of the room temperture. In spite of this, only a few CV_{hot} occur. More details on the results for TABS are described in section 5.2.4

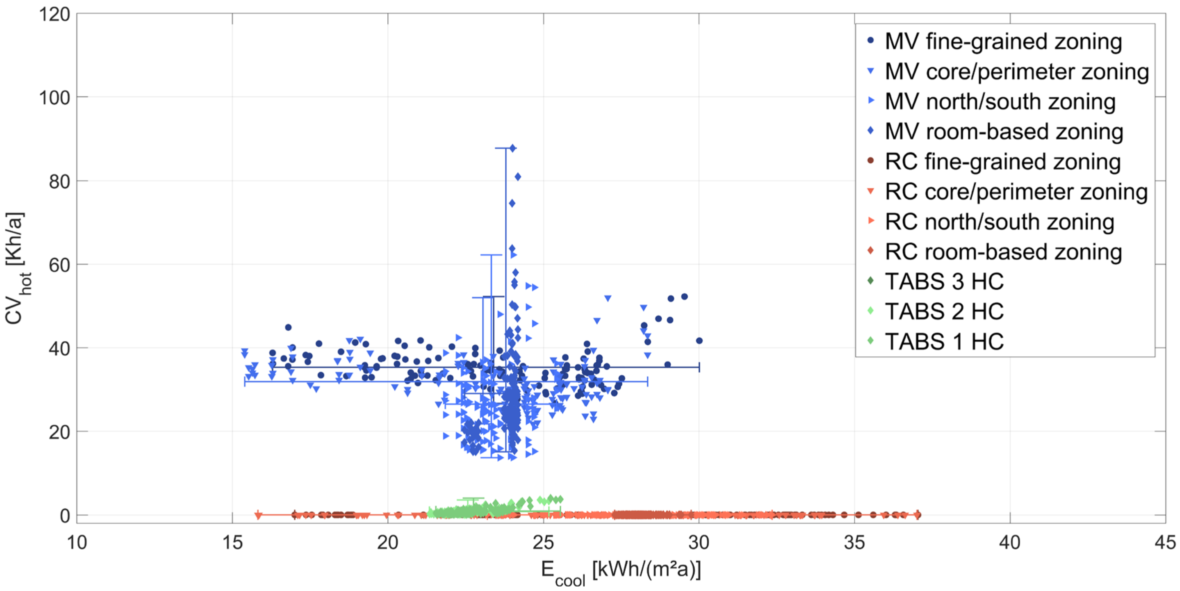


Figure 36. CV_{hot} and E_{cool} for open-plan office airnodes in all variants

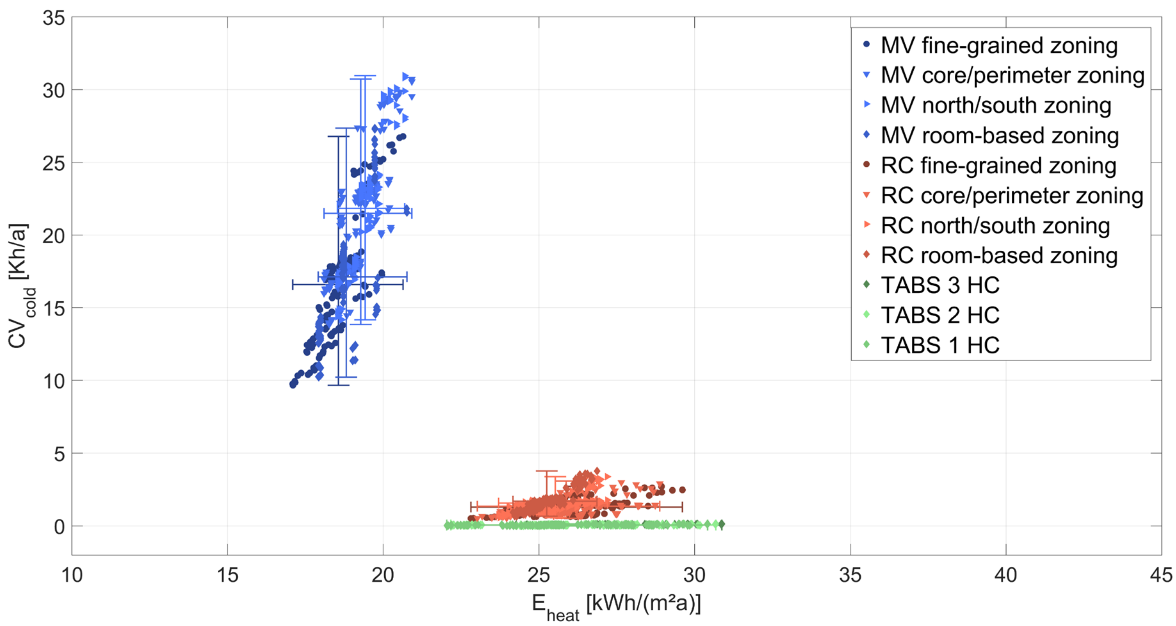


Figure 37. CV_{cold} and E_{heat} for open-plan office airnodes in all variants

Except for variants with RC, less CV_{cold} than CV_{hot} occur in the open-plan office, as illustrated in Figure 37. Moreover, for all HVAC system designs, the range within which E_{heat} lie is much smaller than the range within which E_{cool} lie, even for a high number of control zones. In particular for variants with MV, only small variations of CV_{cold} and E_{heat} occur. More details on the results for MV are described in section 5.2.2.

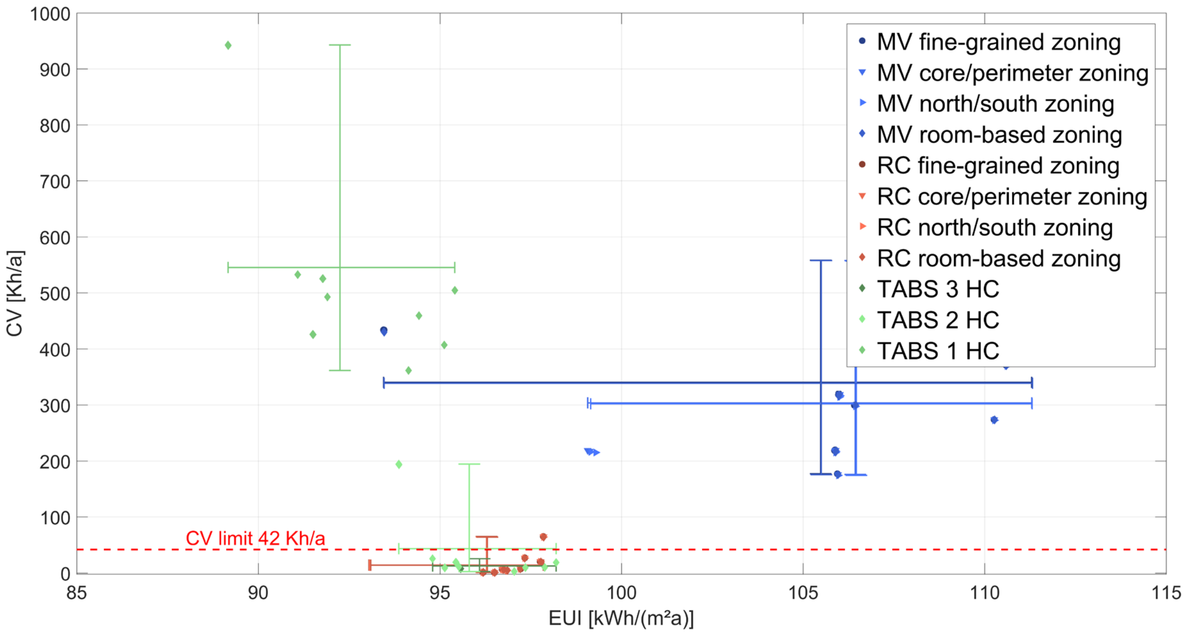


Figure 38. CV and EUI for meeting room airnodes in all variants

Figure 38 compares the CV with the EUI of each airnode in the meeting room for all simulated HVAC system configurations, control zoning strategies and space layout design variants. It should be noted that the values for CV and EUI for the meeting room lie close together for the different control zoning strategies and thus not all values are visible. For the meeting room, almost all CV are CV_{hot} because of the high internal loads during occupancy, described in 4.2.3. In general, for the meeting room only a few variants can remain in the CV limits, which indicates that a secondary heating and cooling system is necessary to serve the high cooling energy demand in a meeting room. The results clearly show that in this setup, especially the MV system is insufficient to keep a meeting room in comfortable conditions. Moreover, high CV in the meeting room are observed if TABS are not zoned, e.g. one HC is used for all airnodes on the floor. The variants with RC show overall good results in thermal comfort in the open-plan office and meeting room.

Robustness

Based on the simulated results, the standard deviations of CV and EUI for each airnode in all space layout design variants are presented. In Figure 39, the results for the open-plan office for each HVAC system configuration and their control zoning strategies are illustrated.

In general, for variants with MV, the standard deviations of the CV are higher than for RC and TABS. This behavior can be explained with the fact that the MV is an air-based heating and cooling system and thus reacts to uncomfortable climate conditions with a change in air temperature. However, CV is calculated with the operative temperature, as described in Equation (5-1)–(5-3). Therefore, MV is unable to keep comfortable conditions especially in areas where the operative and air temperature vary widely, such as areas close to the façade with a high solar radiation. This results in large standard deviations of the CV for different conditions in the office space. In contrast to this, RC and TABS are surface heating and cooling systems and thus can directly influence the operative temperature and can keep the standard deviations of the CV relatively low. The same behavior can be seen for the fine-grained and core/perimeter zoning in the case of the EUI.

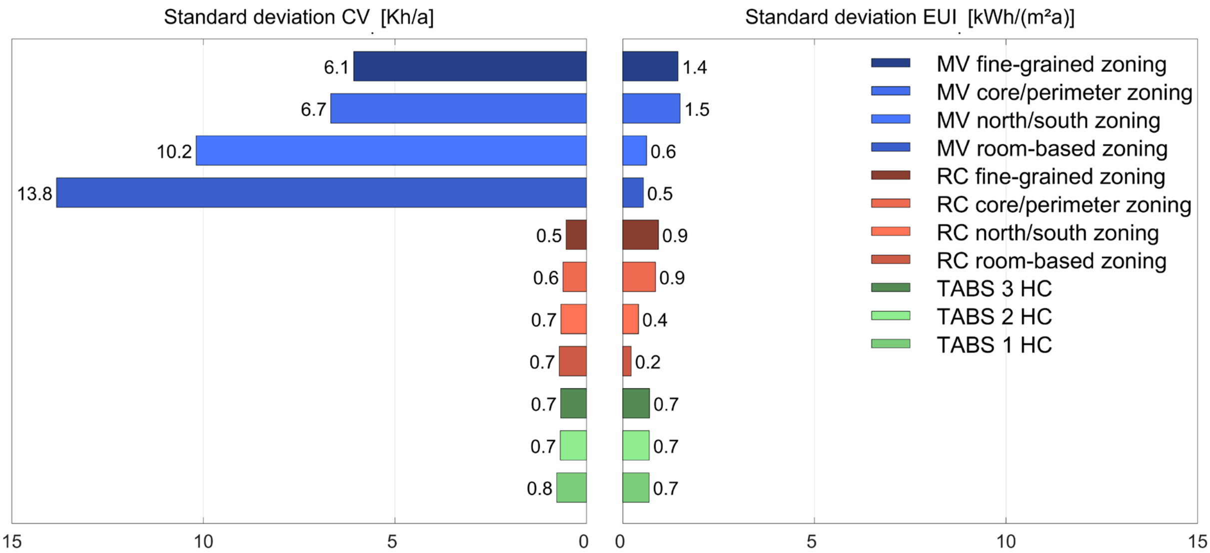


Figure 39. Standard deviations of CV and EUI for open-plan office airnodes

Figure 40 shows the standard deviations of the CV_{hot} and the cooling energy demand and Figure 41 shows the standard deviations of the CV_{cold} and the heating energy demand for the open-plan office. In general, the standard deviations of EUI, heating and cooling energy demand are very low compared to the total EUI, heating and cooling energy demand of each variant. Thus, the differences between the HVAC system configurations and/or the control zoning strategies for the energy demand should not be overestimated.

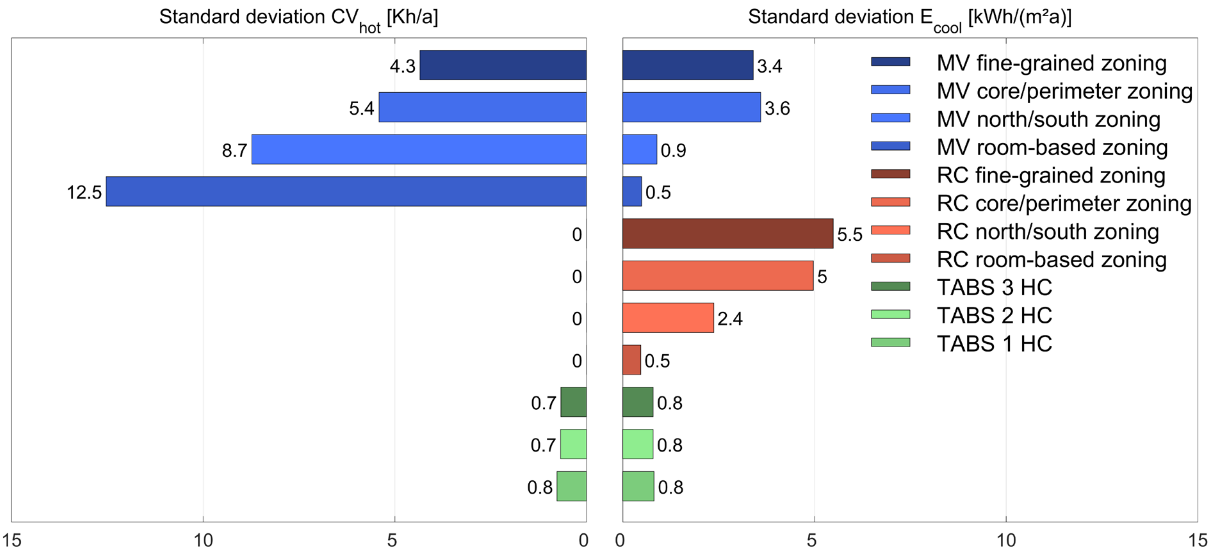


Figure 40. Standard deviations of CV_{hot} and E_{cool} for open-plan office airnodes

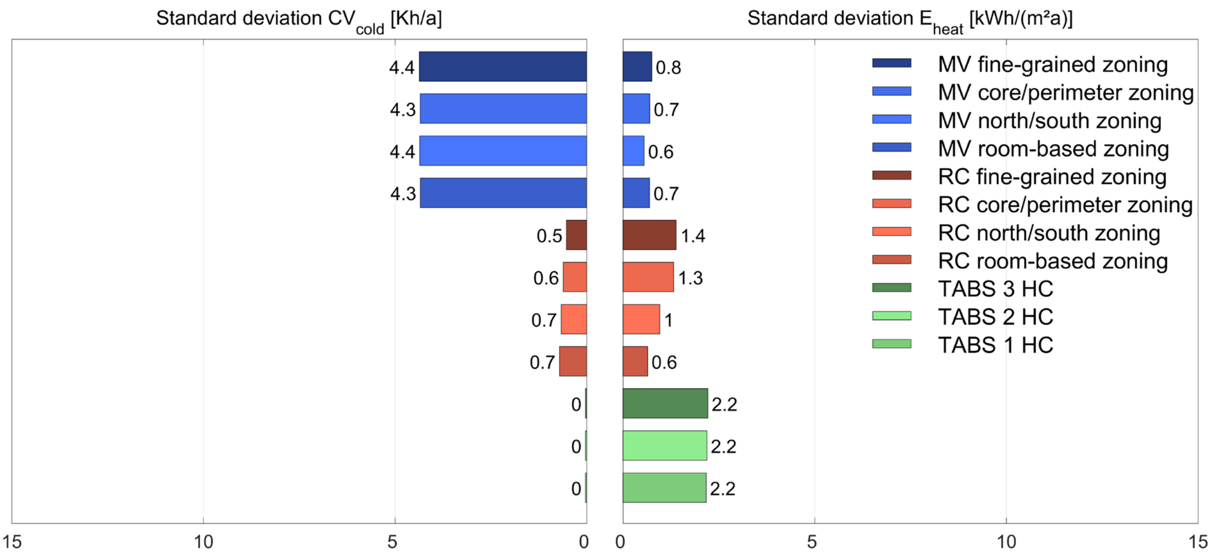


Figure 41. Standard deviations of CV_{cold} and E_{heat} for open-plan office airnodes

For both, CV_{hot} and CV_{cold} the variants with MV have the highest standard deviations, but for CV_{cold} the control zoning strategy does not have an influence on the standard deviations. This is the case, because the differences between the heating energy demand for individual airnodes are already very low ($\leq$ 2 kWh/(m^2·a)) in all control zoning strategies, thus approximately the same amount of CV_{cold} occur in each airnodes of the open-plan office, independent from space layout design and the control zoning. In contrast, for CV_{hot} and CV the standard deviation increases when the number of control zones decreases. This suggests that for variants with less control zones, such as the room-based zoning or north/south zoning, MV is not a robust solution with regard to thermal comfort. Moreover, the standard deviation of EUI and E_{cool} decreases when the number of control zones decreases.

For variants with RC, the standard deviations for the cooling energy demand are in average higher and vary more for different control zoning strategies compared to the other HVAC systems. This can be explained by the possibility to quickly adapt the cooling power provided by RC to local differences in the operative temperature. However, the variation follows the same behavior as for variants with MV: the standard deviation of EUI and E_{cool} when the number of control zones decrease.

For variants with TABS, the standard deviation of CV, CV_{hot}, CV_{cold}, EUI, E_{cool} and E_{heat} is almost constant when the number of control zones changes. This indicates that the control zoning strategy does not have a significant influence on the robustness of thermal comfort and energy efficiency in open-plan office spaces with TABS. In comparison to the other HVAC systems, all standard deviations for thermal comfort and energy demand are low, thus pointing out that TABS are a robust solution for flexible office spaces.

In general, looking at the results for the standard deviations, clear differences can be identified between a surface heating and cooling system, such as RC and TABS, and an air-based heating and cooling system, such as MV. In this case study, the surface heating and cooling systems show better results for thermal comfort in flexible office spaces, because they influence the operative temperature in the room directly, which is used to calculate comfort violations. For an air-based heating system, a control zoning with less zones, such as north/south and room-based zoning should be avoided, because these zoning strategies worsen the ability of the system to react to local differences in the operative temperature. Moreover, the results indicate that systems with high thermal inertia, such as TABS, are beneficial for flexible office spaces, because the system keeps the operative temperature relatively constant throughout the open-plan office, even for changes in the space layout design.

5.2.2 Only Mechanical Ventilation

This section presents the results of variants with the first HVAC system configuration, which only have a *mechanical ventilation* (MV), described in section 4.3.3.

For variants with MV and T_{air} control, the correlation between CV and EUI shows a clear difference between the control zoning strategies in the open-plan office (Figure 42). Each color represents a control zoning strategy and each dot an airnode within all the space layout design variants. As also described in the previous section, the results indicate that for the control zoning strategies with more control zones, such as fine-grained and core/perimeter zoning, the system is more robust in terms of thermal comfort. For fewer control zones, such as north/south and room-based zoning, the system is less sensitive in terms of EUI, but shows higher variations in CV. Furthermore, the crossing point of the lines represents the mean value of CV and EUI for all airnodes in the open-plan office in all space layout design variants. The mean values for CV and EUI lie close together, but the values for each airnode range from 30–106 Kh/a for CV in the room-based zoning and from 47–81 kWh/(m^2·a) for EUI in the fine-grained zoning. This results in a standard deviation of up to 13.8 Kh/a for CV and 1.5 kWh/(m^2·a) for EUI.

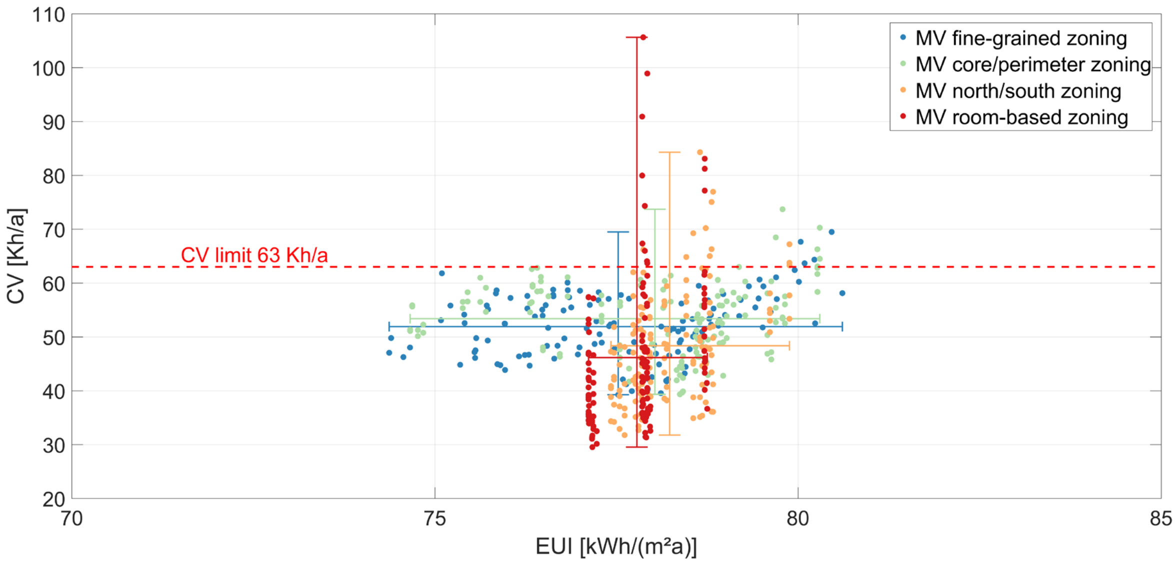


Figure 42. CV and EUI for airnodes in the open-plan office with MV and T_{air} control

These results can be explained by the fact that, the MV controls the air temperature within one control zone according to the mean air temperature measured in the exhaust duct, as described in section 4.3.3. Depending on the size of the control zones, this mean value can differ from the actual temperature in the individual areas within the control zones. Moreover, this uncertainty increase if less control zones are used and the size of each control zone increase accordingly. Thus, the mean values may lie close together, but depending on the size of the control zones, individual values may deviate significantly.

Therefore, the results confirm the importance of choosing an appropriate control zoning strategy for the MV system. If the zoning strategy is not fine-grained enough, it may be challenging to guarantee comfortable indoor climate conditions. This can be seen in Figure 42, where airnodes in the variants with room-based and north/south control zoning strategies exceed the CV limit of 63 Kh/a.

Moreover, to avoid too high CV, a secondary heating and cooling system is recommended for the meeting room, as illustrated in Figure 38.

To identify critical areas in the open-plan office, the space layout designs are investigated in detail (see section 5.3) and the results for space layout design variant no. 3 are illustrated by way of example in Figure 43. For fine-grained, core/perimeter, north/south and room-based zoning, the heating and cooling energy demand of the MV system and the resulting CV in each airnode are compared.

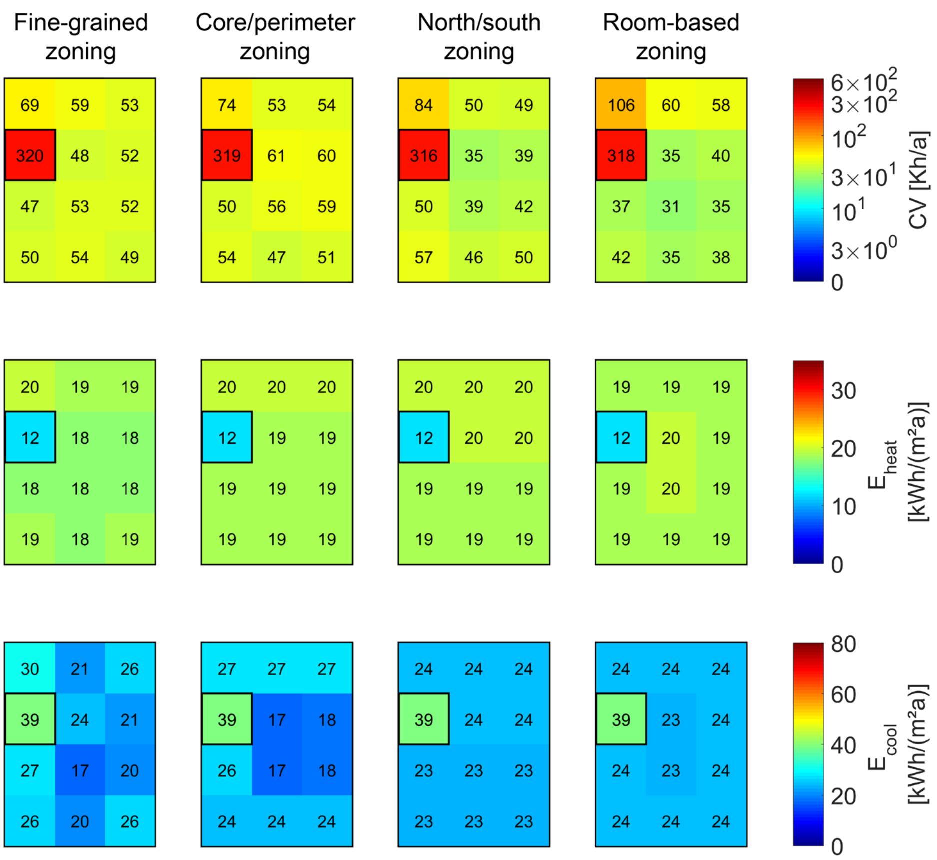


Figure 43. Space layout variant no. 3 with MV – comparison between CV, E_{heat} and E_{cool} for fine-grained, core/perimeter, north/south and room-based zoning

The results indicate that for airnodes with high CV, the comfort violations increase when the number of control zones decrease. For example, for airnode A4 (north-west corner) in the variants with fine-grained zoning, the CV are 69 Kh/a and increase to 106 Kh/a for a room-based zoning, whereas other airnodes improve in CV, such as airnode A6 (core area). This implies that when thermal comfort in office buildings is optimized, the focus should be on critical areas, such as corners or areas that are separated from the open-plan space. More details on the influence of the space layout design on thermal comfort and energy demand in the office space are described in section 5.3.

The results confirm previous findings by the author [81], which show that to evaluate thermal comfort in flexible open-plan offices it is often necessary to use a model with multiple airnodes. For instance, if only one airnode were used to represent the open-plan space, the temperature value used to calculate the CV is the average of the whole space, and thus differences in the local comfort conditions are ignored.

5.2.3 Radiant Ceilings and Basic Mechanical Ventilation

The second HVAC system configuration investigated in this dissertation consists of *radiant ceilings and a basic mechanical ventilation* (RC), described in section 4.3.4.

Figure 44 represents the results for airnodes in the open-plan office with RC and T_{op} control. Due to the CV range of the results (1–3 Kh/a), the axes have been rescaled compared to Figure 43. The distribution of the results with regard to the control zoning strategy is similar to the variants with MV. However, the standard deviations are generally lower, especially for CV.

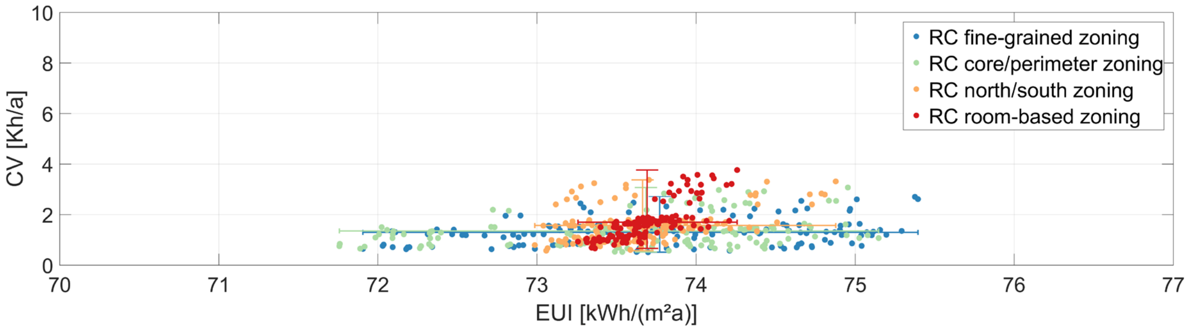


Figure 44. CV and EUI for airnodes in the open-plan office with RC and T_{op} control

The low CV for all variants with RC can be explained by the fact that it is a surface heating and cooling system that directly influences the operative temperature, which in turn is used to calculate the CV in each airnode. Therefore, a low level of CV can be expected if enough heating and cooling power is provided by the RC system and if it is controlled according to the operative temperature obtained from the control zone.

Moreover, the operative temperature is calculated with the mean radiant temperature of the surrounding surfaces (T_{mr}), as described in section 2.2.2. Here, T_{mr} is calculated from the radiation balance in the thermal zone, thus takes into account all surfaces in the open-plan office. If one control zone is assumed for the complete open-plan office (room-based zoning), the sensor to measure T_{op} is placed in the core area of the open-plan office. Thus, T_{mr} takes into account all surfaces within the open-plan office depending on their view factor to the sensor point. If two control zones are assumed for the open-plan office (north/south zoning), two sensors are placed in the office, respectively. However the mean radiant temperature obtained from these two sensors, does not differ significantly, as they take into account the same surfaces in the open-plan office as the sensor for room-based zoning; only the view factor are slightly different due to the different position of the sensors. The same behavior can be observed for different positions of the meeting room. Therefore, the control zoning, including the position and number of sensors in the open-plan office, and the space layout design do not significantly influence the results for RC, which can be seen in the overall low standard deviations for CV.

Even in the meeting room (illustrated in Figure 38), CV remain within the CV limits for all control zoning strategies and space layout design variants, except when the meeting room is located at airnode A4 in the north-west corner. As a result, the space layout design is *fully flexible* with regard to the thermal comfort in meeting room and open-plan office, but particular attention should be paid when the meeting room is located in a corner area.

For the variants with RC, most CV are due to too cold conditions in the airnode (CV_{cold}), because the control zoning strategy mainly influences the cooling energy demand in the airnodes (as illustrated in Figure 45). A too high cooling power provided by the RC can then result in too cold conditions.

Moreover, the RC has in general a higher cooling power than the other HVAC systems investigated in this study and thus can react immediately to temperature changes in the airnode to effectively prevent overheating. This causes higher variations in the cooling energy demand depending on the position of the airnode in the room. As described in section 5.2.1, when the number of control zones decrease, the range within which E_{cool} lie decrease, too. However, this does not have a significant influence on the thermal comfort, as illustrated in Figure 44, because CV for fine-grained zoning is not significantly lower than CV for room-based zoning.

To identify areas in the open-plan office where the E_{heat} or E_{cool} can be above average, the space layout designs are investigated in detail (see section 5.3) and the results for space layout design variant no. 3 are illustrated by way of example in Figure 45. For fine-grained, core/perimeter, north/south and room-based zoning, the heating and cooling energy demand of the RC and the resulting CV in each airnode are compared. The results for CV confirm the previously mentioned assumption that the control zoning strategy has no significant influence. Moreover, the results show a high cooling energy demand in the corner areas for fine-grained zoning. As the number of control zones decrease, the E_{cool} is distributed more evenly throughout the open-plan office. The same behavior can be observed for the heating energy demand.

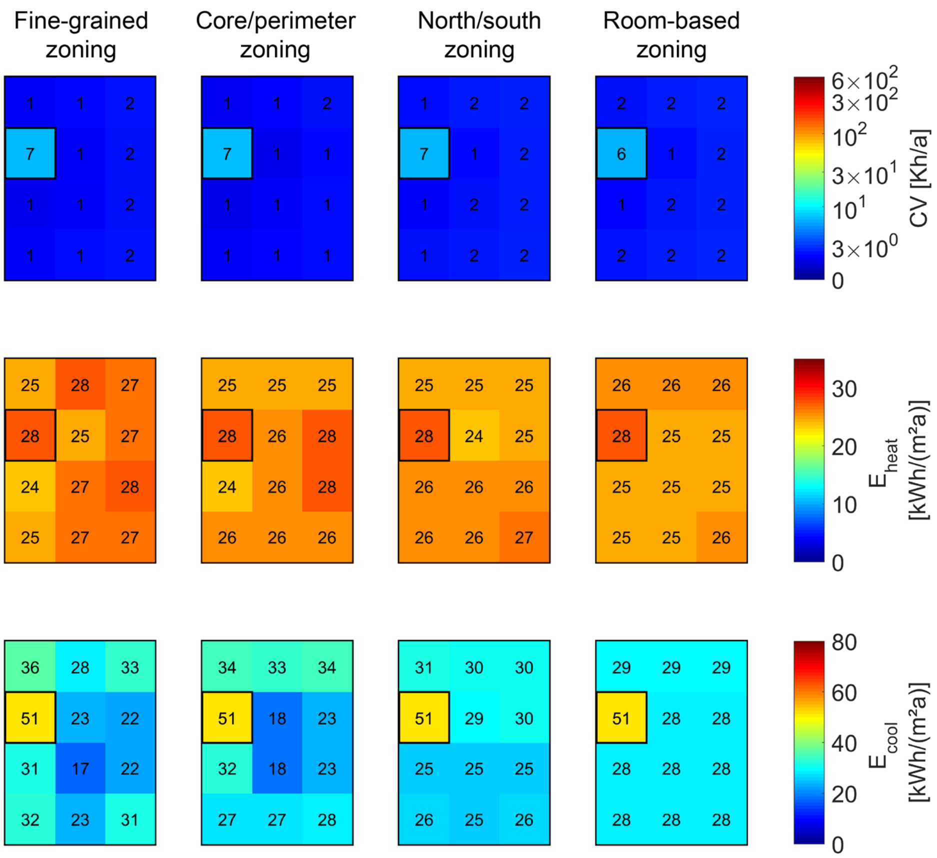


Figure 45. Space layout variant no. 3 with RC – comparison between CV, E_{heat} and E_{cool} for fine-grained, core/perimeter, north/south and room-based zoning

5.2.4 TABS and Basic Mechanical Ventilation

The third HVAC system configuration investigated in this dissertation consists of *TABS and a basic mechanical ventilation* (TABS), described in section 4.3.5.

Figure 46 represents the results for airnodes in the open-plan office with TABS. Due to the CV range of the results (0–4 Kh/a), the axes have been rescaled compared to Figure 42. As the control zoning strategies are based on different heating and cooling curves (HC), which are described in section 4.3.5, not every control zoning strategy that has been investigated for MV and RC is realizable. Thus, the results can only be compared to a limited extent with the ones for MV and RC.

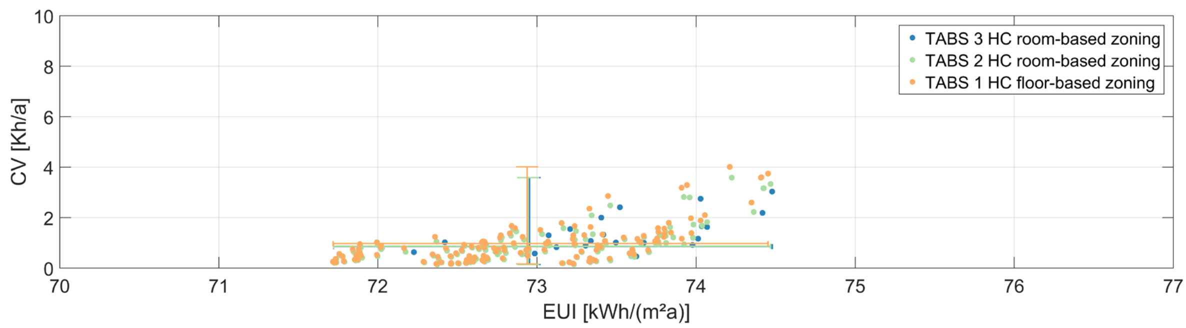


Figure 46. CV and EUI for airnodes in the open-plan office with TABS

The main difference between the control zoning strategies can be seen in the results for the meeting room, illustrated in Figure 38. For the floor-based zoning with the same HC for all airnodes including the meeting room, high CV are obtained in the meeting room, and low CV in the open-plan office. To improve thermal comfort in the meeting room, different HC are applied to each room. Further improvement can be obtained in the meeting room by employing a room-based zoning with three HC, which applies a third HC when the meeting room is positioned in the core area of the floor (airnodes A6 and A7). As a result, the space layout design is *fully flexible* in terms of the thermal comfort in the open-plan office, but particular attention should be paid to the meeting room, especially when it is positioned in the core area of the floor.

Figure 47 shows the comparison of the operative room temperature (T_{op}) depending on the outside air temperature (T_{air}) for all variants with TABS using three, two or one HC. The red lines indicate the comfort limits as described in section 4.3.1. It shows that even for a low ambient temperature, most CV are due to overheating with increasing number of CV_{hot} as the number of control zones or HC decrease. However, it should be noted that the CV_{hot} mainly occur in the meeting room, due to its high internal gains, as described in section 4.2.3.

Therefore, it is not recommended to use only one control zone or HC for the whole floor, including open-plan office and meeting room.

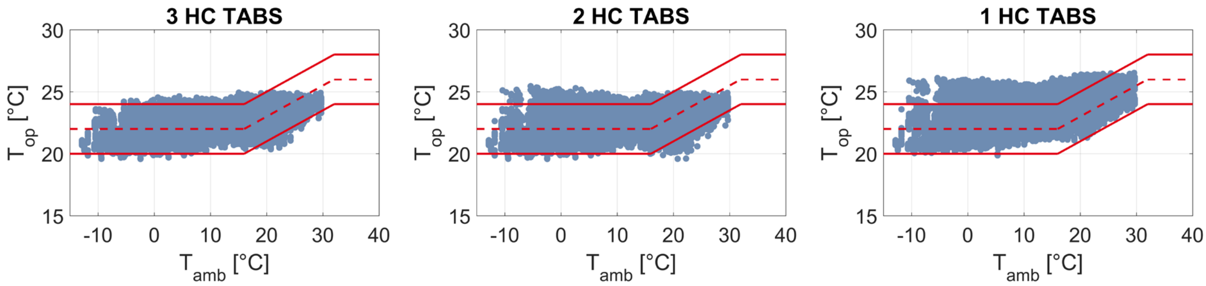


Figure 47. Comparison of the operative temperature (T_{op}) for variants with TABS using 3 HC, 2 HC and 1 HC as function of the ambient air temperature (T_{amb})

To show the thermal behavior of all airnodes in the office space and their spatial distribution, the results for CV, E_{heat} and E_{cool} are illustrated in Figure 48 for the space layout design variant no. 7. It is clearly shown that the HC do not have a significant influence on the thermal comfort in the open-plan office, but on that in the meeting room. Moreover, the heating and cooling energy demand are evenly distributed, except for the areas in the north/west corner, where more heating and cooling energy is requires. This effect can be explained on the one hand by the corner position of the airnode, which leads to higher thermal gains and losses through the façade, and on the other hand by the adjacent meeting room, which prevents sufficient air exchange with the open space.

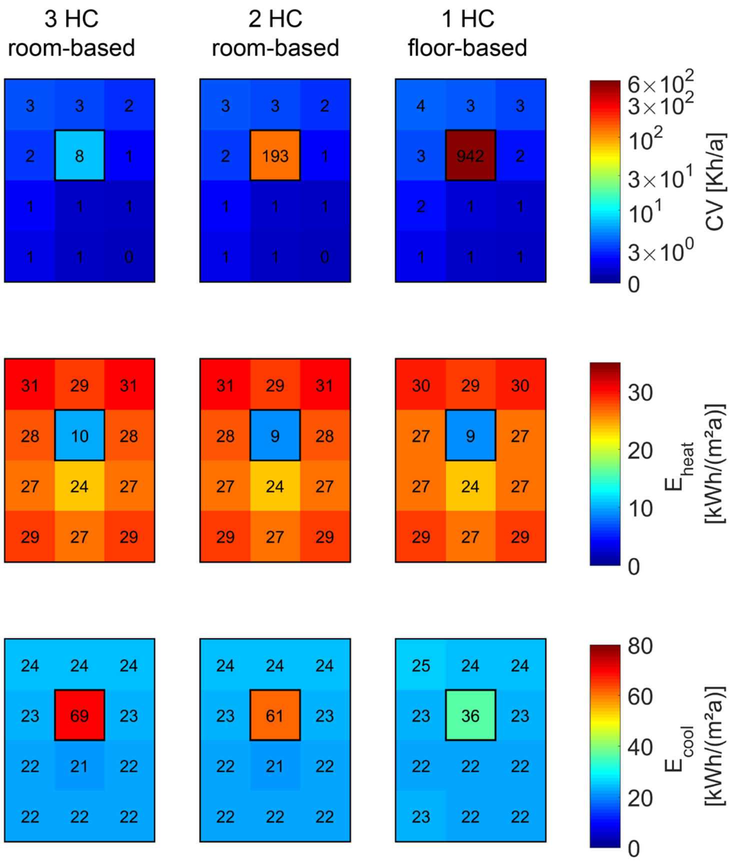


Figure 48. Space layout variant no. 7 with TABS – comparison between CV, E_{heat} and E_{cool} for 3 HC, 2 HC and 1 HC

5.2.5 Influence of the Control Zoning Strategy

In this section, the influence of the control zoning strategy on thermal comfort, energy demand and robustness is discussed in detail. In order to study this influence in an isolated manner, all other flexible design parameters (space layout design, HVAC system configuration and the controlled variable) are assumed to be constant. Based on the results presented in the previous sections, it can be said the influence of the control zoning strategy on the mentioned criteria depends strongly on the HVAC system configuration. Thus, each HVAC system configuration is investigated individually and the influence of space layout changes are not taken into account.

First, an overview of the influence of the control zoning strategy for each HVAC system configuration is presented, to summarize what was discussed in the previous sections. Afterwards, the results for the variants simulated with an ideal heating and cooling system (IHC) are described. Using the IHC allows to analyze only the influence of the control zoning strategy, without considering inertia and limits of a specific HVAC system.

HVAC System Configurations

For the variants with MV, the control zoning strategy has a significant influence on CV and EUI in the open-plan office, especially on the share of CV_{hot} and E_{cool}. When the number of control zones decrease, the standard deviation of CV_{hot} increases from 4.3 Kh/a to 12.5 Kh/a and the standard deviation of E_{cool} decreases from 3.4 kWh/(m^2·a) to 0.5 kWh/(m^2·a), illustrated in Figure 40. The mean value of CV_{hot} for all airnodes within the open-plan office does not show a significant dependency from the control zoning strategy, because they lie close together for the different control zoning strategies. However, for the "critical areas" in the open plan office, such as corner areas, it is clearly shown that less control zones lead to higher comfort violations, illustrated in Figure 43. For the cooling energy demand, more control zones lead to a higher range within which the cooling energy demand lie. In this case for variants with fine-grained zoning, a range from 16.3 kWh/(m^2·a) to 30.1 kWh/(m^2·a) occur with a standard deviation of 3.4 kWh/(m^2·a), whereas for the room-based zoning, only a range from 22.5 kWh/(m^2·a) to 25.2 kWh/(m^2·a) occur with a standard deviation of 0.5 kWh/(m^2·a). In comparison to the variants with RC and TABS, the control zoning strategy influences the variants with MV most significantly.

For the variants with RC, the control zoning strategy has no significant influence on CV in the open-plan office. However, the range within which the EUI lies, including heating and cooling energy demand, depends on the control zoning strategy. The strongest effect can be observed for the cooling energy demand. Here, the range within which the cooling energy demand for the different airnodes lie decreases for a decreasing number of control zones and accordingly the standard deviation decreases from 5.5 kWh/(m^2·a) to 0.5 kWh/(m^2·a). Thus, less control zones lead to a more evenly distributed cooling energy demand across all airnodes within the open-plan office.

For the variants with TABS, the control zoning strategy has no significant influence on CV and EUI in the open-plan office. Only for corner areas and/or areas with an adjacent meeting room, small effects on CV can be observed. For the meeting room, a separated control zone should be realized to prevent the room from overheating. Moreover, different HC should be applied for meeting rooms positioned in the core areas, compared to meeting rooms positioned in the perimeter areas of the office space. Thus, it can be said that the control zoning strategy has an influence of the CV and EUI of the meeting room. However, it should be noted that the control strategy does not take into account interior climate conditions, but instead uses the ambient air temperature to calculate the supply temperature for the TABS.

In summary, the configuration of the HVAC system itself has the greatest impact on the results for the different control zoning strategies. This result can be attributed to the different thermal inertia and calculation methods of the control strategy for the different HVAC systems, described in sections 4.3.3–4.3.5.

Ideal Heating and Cooling System

To analyze only the influence of the control zoning strategy on thermal comfort and energy demand and robustness, without considering thermal inertia and limits of a specific HVAC system configuration, the building model is simulated with an ideal heating and cooling system (IHC). The simulation setup for these variants is described in 4.3.2.

Figure 49 shows the results for all variants with IHC. Here, the CV are correlated to the EUI for each control zoning strategy. Each dot represents the results for one airnode in the open-plan office. The results are evaluated for all space layout design variants. Compared to the realistic HVAC system configurations presented before, it can be said that the results for IHC follow the same structure as the results for MV.

For the fine-grained zoning, no CV occur because the IHC conditions each airnode in an idealized way. Here, the largest variation in EUI for all control zoning strategies are obtained, with a range of 2.2 kWh/(m^2·a). This range is still small compared to the total EUI for the office building and thus does not have a significant impact on it. The results for the core/perimeter zoning and the for the north/south zoning, lie close together, whereas the CV are slightly higher for the north/south zoning. The outliers in all control zoning strategies are airnodes located in building corners (A1, A4, A9, A12). For the room-based zoning, the largest differences in CV for all control zoning strategies are obtained, with a range of 71 Kh/a, starting from 18 Kh/a to 89 Kh/a. In this case, some airnodes lie above the CV limit of 63 Kh/a. Thus, room-based zoning is not suitable for all space layout design variants.

In summary, for all airnodes located in the open-plan office, with a decreasing number of control zones, the range within which the CV lies increases, while the range within which the EUI lies decreases. Also the mean value of CV for all variants with the same control zoning strategies increase when the number of control zones decrease. Therefore, a sufficiently high number of control zones are recommended for an open-plan office space to avoid CV.

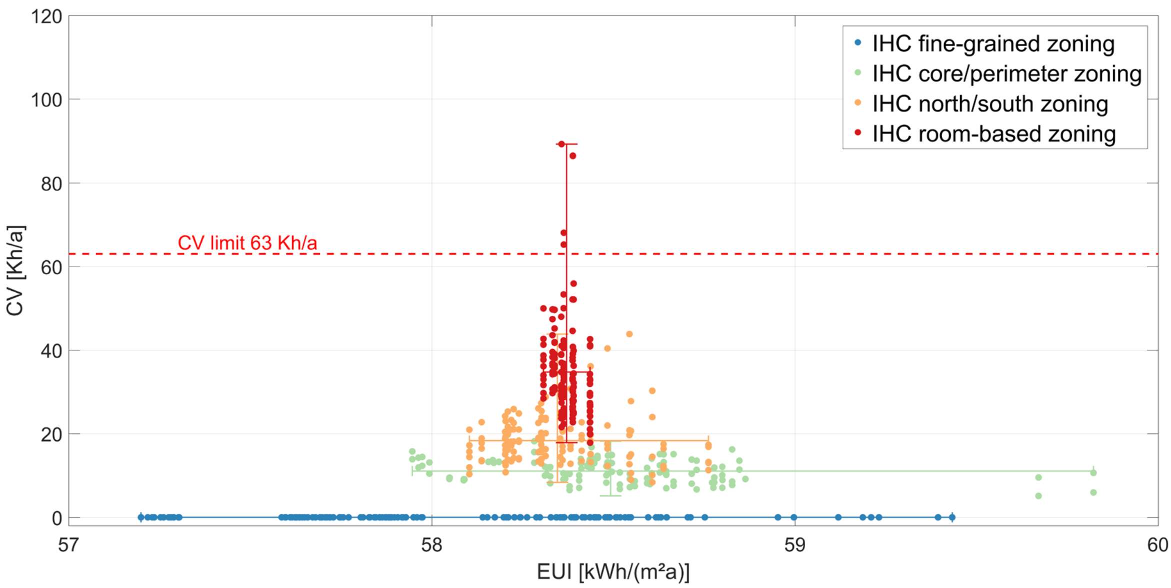


Figure 49. Comparison of control zoning strategies for the open-plan office with an ideal heating and cooling system

To conclude, for the MV and IHC the control zoning strategy has a significant influence on the results. These influence result from the calculation method of the control zone: Each airnode within one control zones is supplied with the heating and cooling energy calculated with the mean temperature of all airnodes within this control zone. However, these mean temperature can differ from the actual temperature in the airnodes. Consequently, these airnodes are not supplied with enough heating or cooling, which results in comfort violations.

5.2.6 Influence of the Controlled Variable

In this section, the influence of the controlled variable on the result for the variants with MV and RC are investigated. In this case, all building parameters and assumptions remain the same for all variants investigated, except for the controlled variable.

Mechanical Ventilation

As described in section 4.3.3, the MV in the case study is controlled by the air temperature in the exhaust duct (T_{air}). The following is a comparison of the results if the operative room temperature (T_{op}) is used as the controlled variable instead of T_{air}. In Figure 50, the results for the airnodes in the open-plan office with MV are compared for T_{air} and T_{op} as the controlled variable. Figure 51 presents the results for the meeting room, respectively.

For both the open-plan office and meeting room, the CV decrease if T_{op} is used as the controlled variable instead of T_{air}. For the open-plan office, the standard deviations and ranges of CV decrease, too. Thus, the airnodes of the open-plan office in all variants remain within the CV limit of 63 Kh/a when T_{op} is used as the controlled variable. This can be explained with the fact that T_{op} is used to calculate the comfort violations. Thus, if T_{op} is used as the controlled variable, the system can directly response to the thermal comfort in the office. However, the influence of the control zoning strategy on the results are independent from the controlled variable: Less control zones leads to higher standard deviations and ranges of CV and lower standard deviations and ranges of EUI.

For the meeting room, the EUI increases if T_{op} is used as the controlled variable instead of T_{air}. However, the standard deviations and ranges of CV and EUI remain the same independent from the controlled variable that is used in the meeting room. This is the case, because the indoor climate in the meeting room is mainly influence by its high internal and the solar gains, which both remain unchanged. None of the used controlled variables allow the meeting room to stay within in the CV limit of 42 Kh/a. It should be noted that the values for CV and EUI for the meeting room lie close together for the different control zoning variants, thus only the values for the room-based zoning are visible in Figure 51.

Moreover, it is important to mention that the calculation for the control zoning strategy for the variants with MV, presented in section 4.3.1, is based on the temperature in the exhaust air ducts. In reality, the operative temperature needs to be measured in the room. Thus, this comparison is just hypothetical and has a limited application in practice.

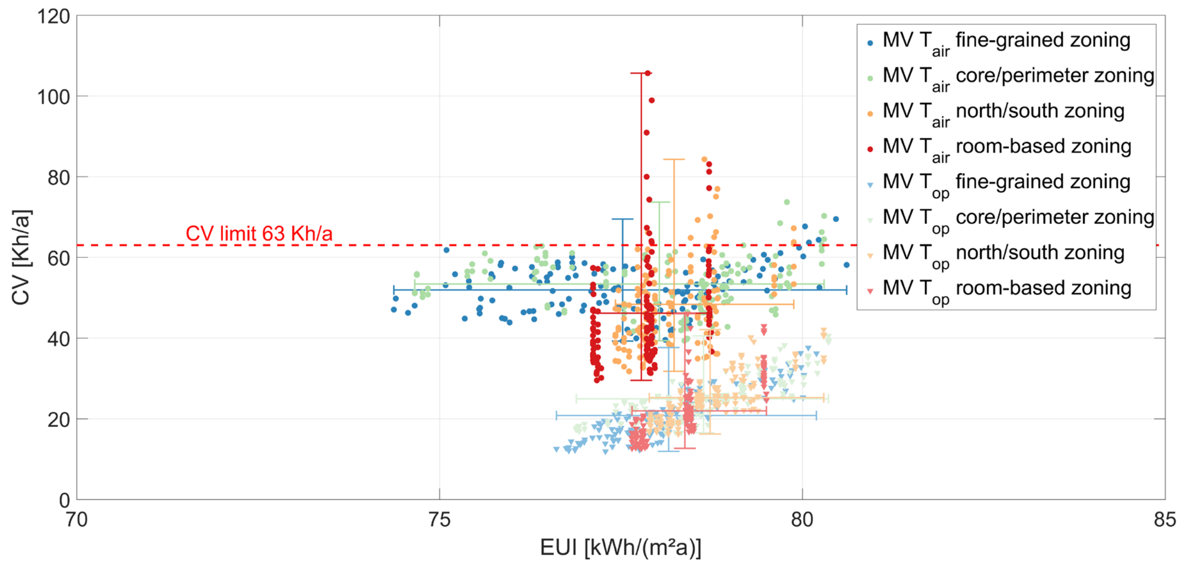


Figure 50. Comparison between T_{air} and T_{op} as the controlled variable for airnodes in the open-plan office with MV

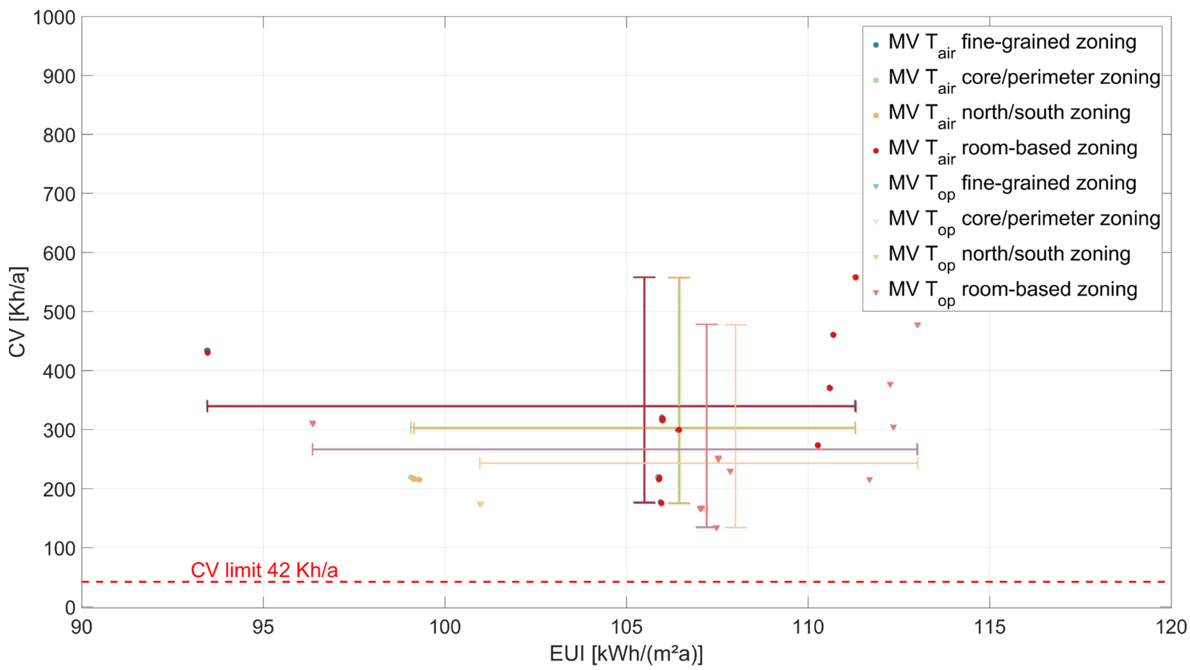


Figure 51. Comparison between T_{air} and T_{op} as the controlled variable for airnodes in the meeting room with MV

Radiant Ceilings

As described in section 4.3.4, the RC in this case study is controlled by the operative temperature (T_{op}) measured with a sensor placed in each control zone. The following is a comparison of the results if the air temperature (T_{air}) is used as the controlled variable instead of T_{op}. In Figure 52, the results for the airnodes in the open-plan office with RC are compared for T_{op} and T_{air} as the controlled variable. Figure 53 presents the results for the meeting room, respectively.

For both the open-plan office and meeting room, the EUI slightly increase if T_{air} is used as the controlled variable instead of T_{op}. For the open-plan office, the standard deviations and ranges of CV increase for the variants with north/south and room-based zoning, too. Especially for room-based zoning the control based on T_{air} causes some outliers. Here, the air temperature in the airnode deviates from the operative temperature and results in CV if a coarse control zoning is used. However, for the other airnodes, the influence of the control zoning strategy on the results are independent from the controlled variable: Less control zones lead to higher standard deviations and ranges of CV and lower standard deviations and ranges of EUI.

For the meeting room, also the EUI and the CV slightly increase if T_{air} is used as the controlled variable instead of T_{op}. It should be noted that the values for CV and EUI for the meeting room in the different control zoning variants lie close together, thus only the values for the room-based zoning are visible in Figure 53.

As a result, the control based on T_{op} is recommend for office spaces with RC, even through a control based on T_{air} still generates good results for thermal comfort and energy demand in this case study.

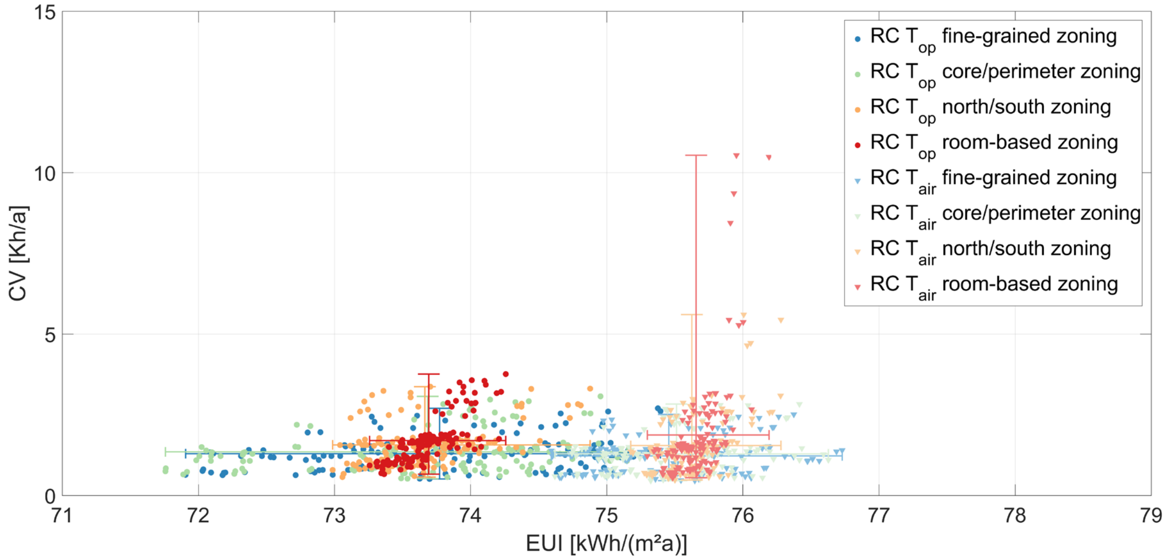


Figure 52. Comparison between T_{op} and T_{air} as the controlled variable for airnodes in the open-plan office with RC

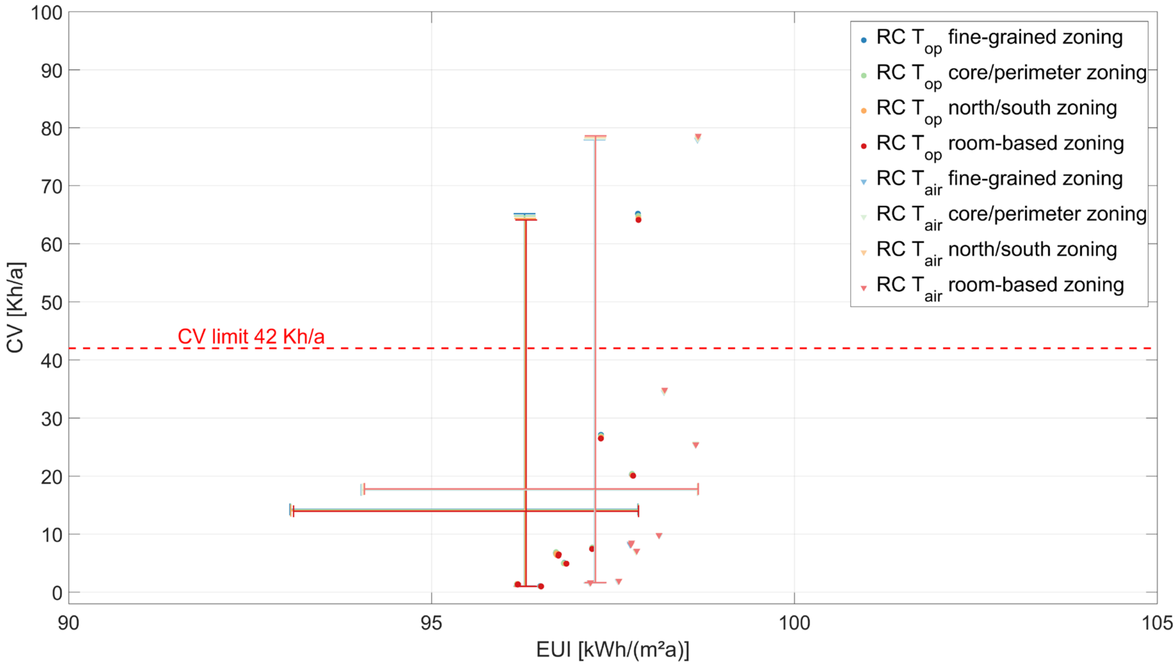


Figure 53. Comparison between T_{op} and T_{air} as the controlled variable for airnodes in the meeting room with RC

5.3 Influence of the Space Layout Design

In this section, the influence of the space layout design on thermal comfort and energy demand of the office space is described. For all variants, the space layout design changes according to the defined variants no. 1–12, illustrated in Figure 54 (left side). The evaluation is carried out separately for each HVAC system and a distinction is made between the results for the meeting room and the open-plan office. As a result, a recommendation is given for each HVAC system design regarding the flexibility of the space layout design and its impact on thermal comfort and energy demand.

As illustrated in Figure 54 (right side), the airnodes A1, A4, A9 and A12 are referred to as "corner areas", the airnodes A6 and A7 are referred to as "core areas" and all other airnodes are referred to as "perimeter areas". Moreover, the space layout design is called "flexible" if thermal comfort and energy demand does not significantly change when the space layout design changes, as described in section 5.1.3.

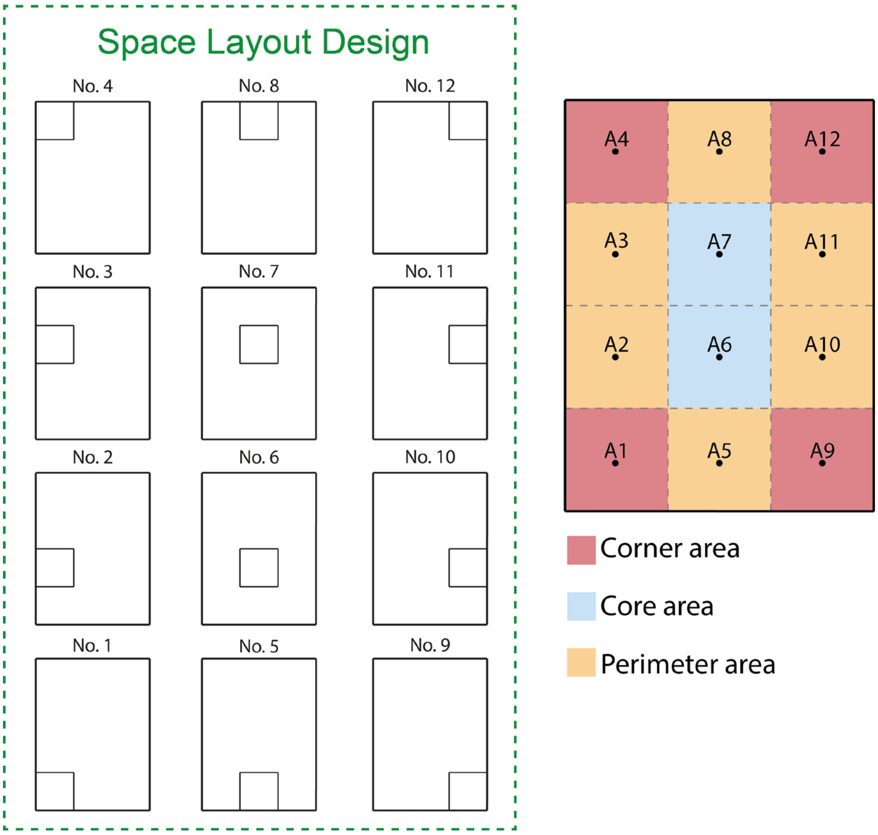


Figure 54. Space layout design as part of the flexible design parameters

5.3.1 Only Mechanical Ventilation

Thermal Comfort

Figure 55 shows the CV for the space layout design variants no. 1–12 with a fine-grained zoning and a room-based zoning of the MV system. In addition, the CV for a core/perimeter and a north/south zoning of the MV system is shown in Appendix D.

For the meeting room, it is clearly shown that its position has a significant influence on its thermal comfort, because the influence of the solar radiation depends on the position of the meeting room. In this case study, only a mechanical ventilation is used for heating and cooling of the meeting room, leading the CV to exceed the limit of 42 Kh/a for all variants. Therefore, a secondary heating and cooling system is recommended for the meeting room.

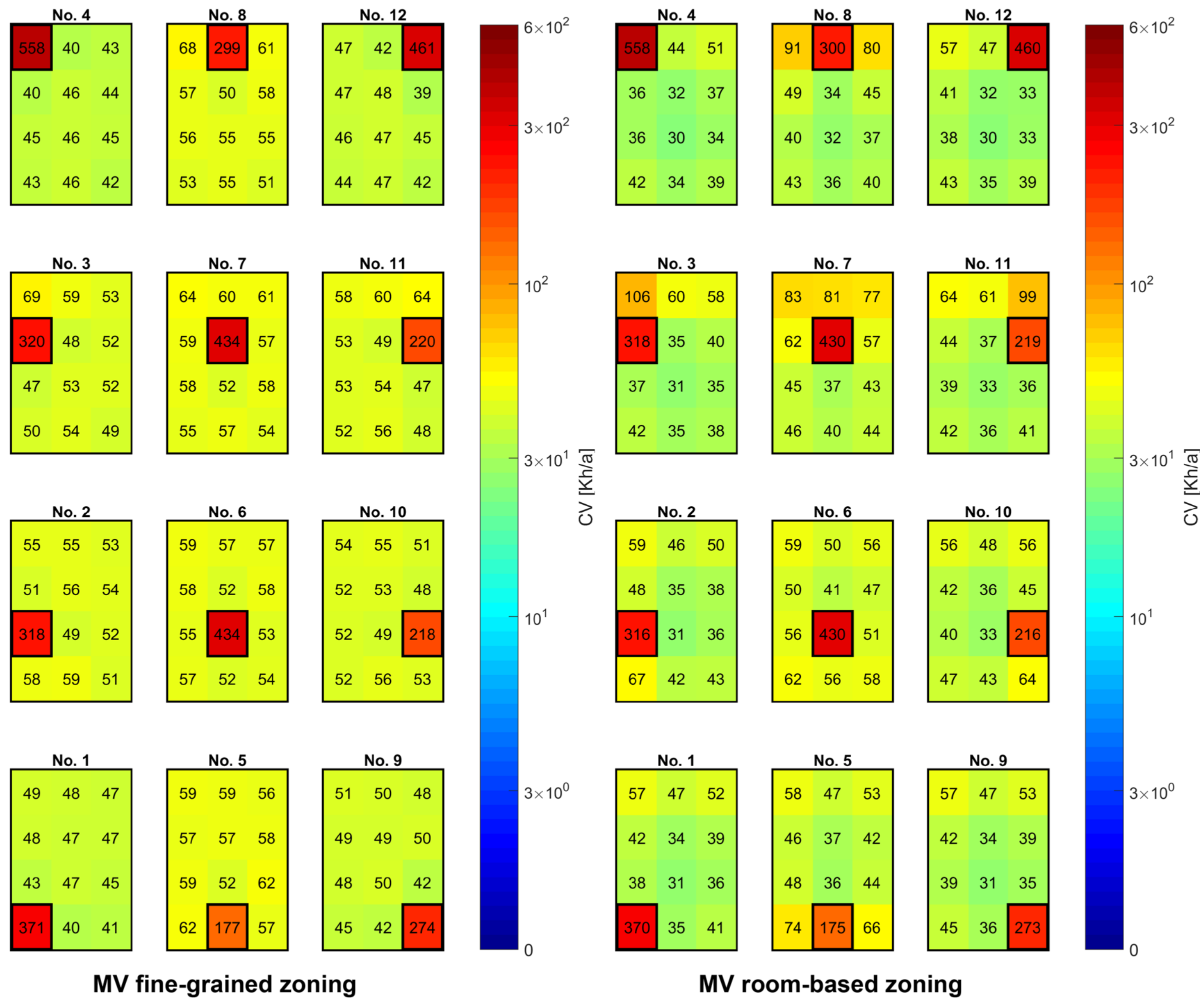


Figure 55. MV – comparison of CV for space layout variants no. 1–12 for fine-grained and room-based zoning

For the open-plan office, the influence of the space layout design on the thermal comfort depends on the zoning strategy of the MV system. For fine-grained zoning, the position of the meeting room and thus the space layout design has little influence on thermal comfort in the open-plan office. Using fine-grained zoning, the MV can condition the airnodes individually so that the system can compensate for changes in the space layout design.

For room-based zoning, the space layout design has a significant influence on thermal comfort, especially in critical areas, as mentioned in section 5.2.2. Here, the heating and cooling provided by the MV is calculated based on the mean air temperature in the control zone, which is the complete open-plan office for a room-based zoning. However, this mean air temperature can differ from the temperature in individual areas of the open-plan office. Thus, the system does not provide the required power in these critical areas, leading to comfort violations. This effect can be enhanced by the position of the meeting room, as it reduces the exchange of air with the adjacent areas, thus increasing the temperature difference between the critical area and the rest of the open-plan office.

In general, for a decreasing number of control zones the influence of the space layout design on the thermal comfort in the open-plan office increases. For less control zones, high CV occur in critical areas, such as the corner areas.

Energy Demand

In Figure 56, the heating and cooling energy demand for the space layout design variants no. 1–12 with a fine-grained zoning of the MV system are illustrated. In addition, the EUI for a fine-grained, a core/perimeter, a north/south and a room-based zoning of the MV system is shown in Appendix D.

For the meeting room, the influences of the space layout design on heating and cooling energy demand is equal for all control zoning strategies. In contrast, for the open-plan office the influence of the space layout design on the E_{cool} decreases when the number of control zones decreases.

The position of the meeting room has a significant influence on its heating energy demand: If the meeting room is positioned in the corner areas, E_{heat} is higher because of the heat loss through the façade. If the meeting room is positioned in the core areas, less heating is required because it is surrounded by the heated open-plan office, thus the heat loss is through the interior drywalls is low. In contrast, the position of the meeting room has no significant influence on its cooling energy demand, as this is mainly determined by its high internal gains, which are the same in all meeting room positions.

For the open-plan office, the space layout design has no significant influence on the heating energy demand, as illustrated in Figure 56: For each airnode, only small variations (≤ 2 kWh/(m^2·a)) are recognizable if the space layout design changes. In contrast, the space layout design has an influence on the cooling energy demand of the MV system with a fine-grained zoning. If the meeting room is positioned in an adjacent airnode, E_{cool} in the open-plan office airnodes is higher than for the airnodes with no adjacent meeting room, because of the heat transfer from the warmer meeting room, which has higher internal gains from people and equipment, to the open-plan office. Moreover, if the air exchange with other airnodes in the open-plan office is partially blocked by the position of the meeting room, E_{cool} is higher, too. In this case study, the corner areas are most sensitive to variations in E_{cool} when the space layout design changes.

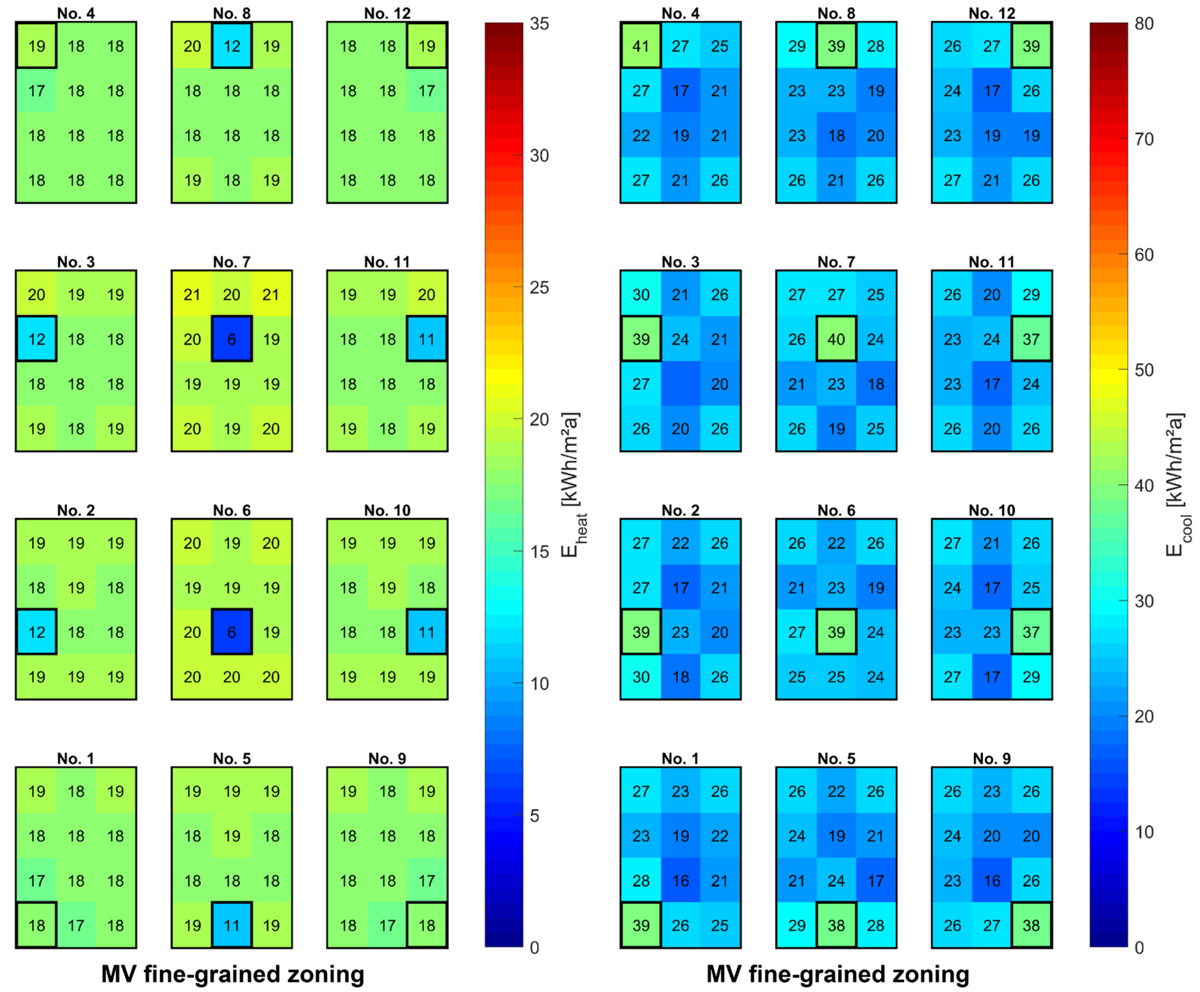


Figure 56. MV – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 for fine-grained zoning

Flexibility of Space Layout Design

For variants with MV, the space layout design is not flexible regarding the meeting room's thermal comfort and energy demand, because it varies strongly with its positions. However, regarding the open-plan office, the space layout design is flexible if an appropriate number of control zones are implemented, such as fine-grained zoning or core/perimeter zoning.

5.3.2 Radiant Ceilings and Basic Mechanical Ventilation

Thermal Comfort

Figure 57 shows the CV for the space layout design variants no. 1–12 with a fine-grained zoning and a room-based zoning of the RC. In addition, the CV for a core/perimeter and a north/south zoning of the RC is shown in Appendix D.

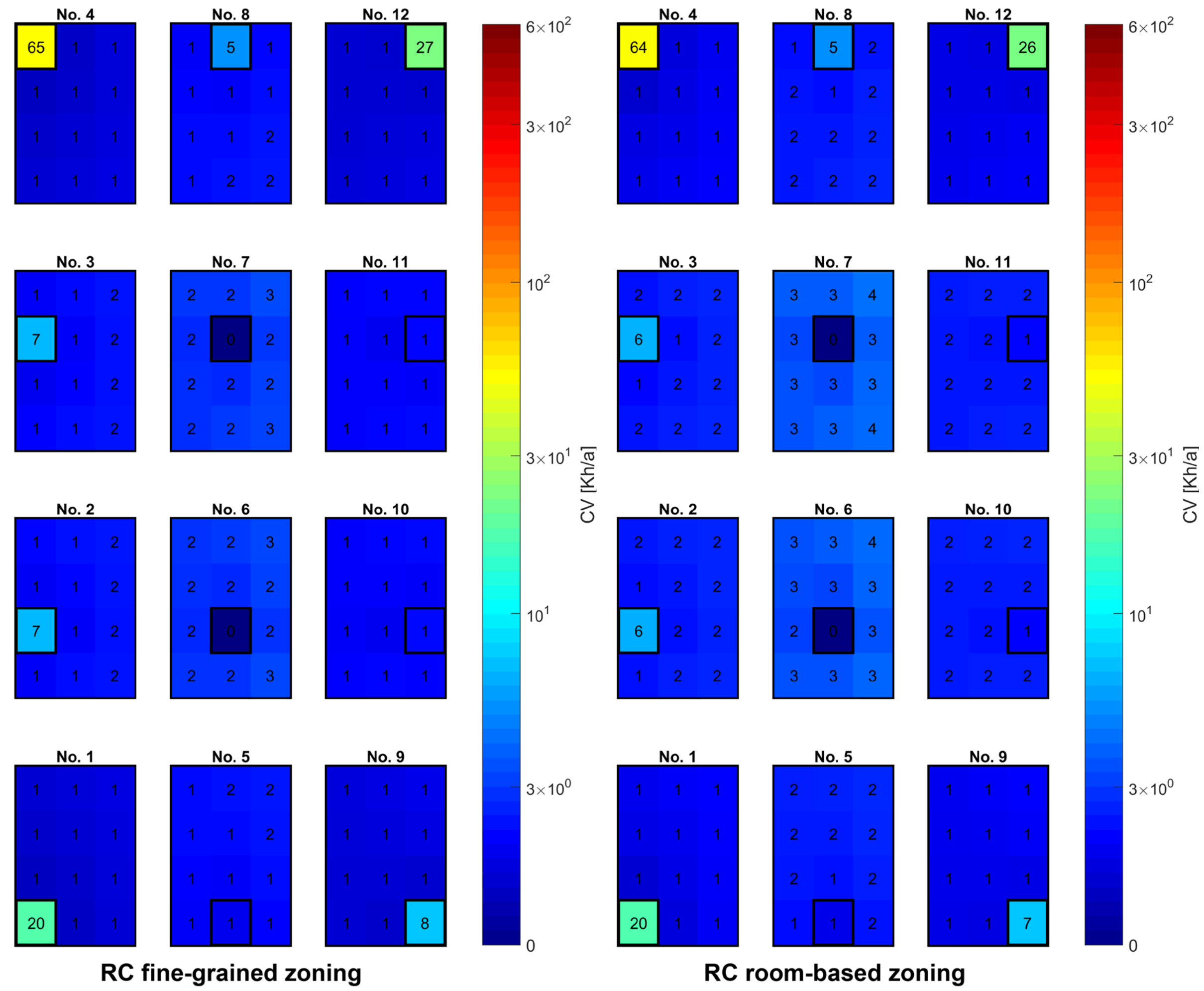


Figure 57. RC – comparison of CV for space layout variants no. 1–12 for fine-grained and room-based zoning

For the meeting room, it is clearly shown that its position has a significant influence on its thermal comfort, independent from the control zoning strategy. As mentioned before, this can be explained by the influence of the solar radiation, which differs depending on the position of the meeting room. Furthermore, the control zoning strategy does not affect the conditioning of the meeting room. For all variants, the meeting room remains within the CV limit of 42 Kh/a, except when it is located at airnode A4. Moreover, it should be noted that all CV are due to overheating in the meeting room. However, high thermal comfort can always be reached when the meeting room is positioned in the core areas, because in this position no solar gains are heating the room.

In contrast, for the open-plan office all CV are CV_{cold}, as explained in the previous sections. In this case, the space layout design has no significant influence on CV in the open-plan office, independent from control zoning strategy, as explained in section 5.2.3. This results in a maximum CV range for each airnode of 1–4 Kh/a depending on layout the space layout design.

Energy Demand

In Figure 58, the heating and cooling energy demand for the space layout design variants no. 1–12 with a fine-grained zoning of the RC system are illustrated. In addition, the heating and cooling energy demand for a core/perimeter, a north/south and a room-based zoning of the RC system are shown in Appendix D. Furthermore, the EUI for a fine-grained and a room-based zoning of the RC system is shown in Appendix D.

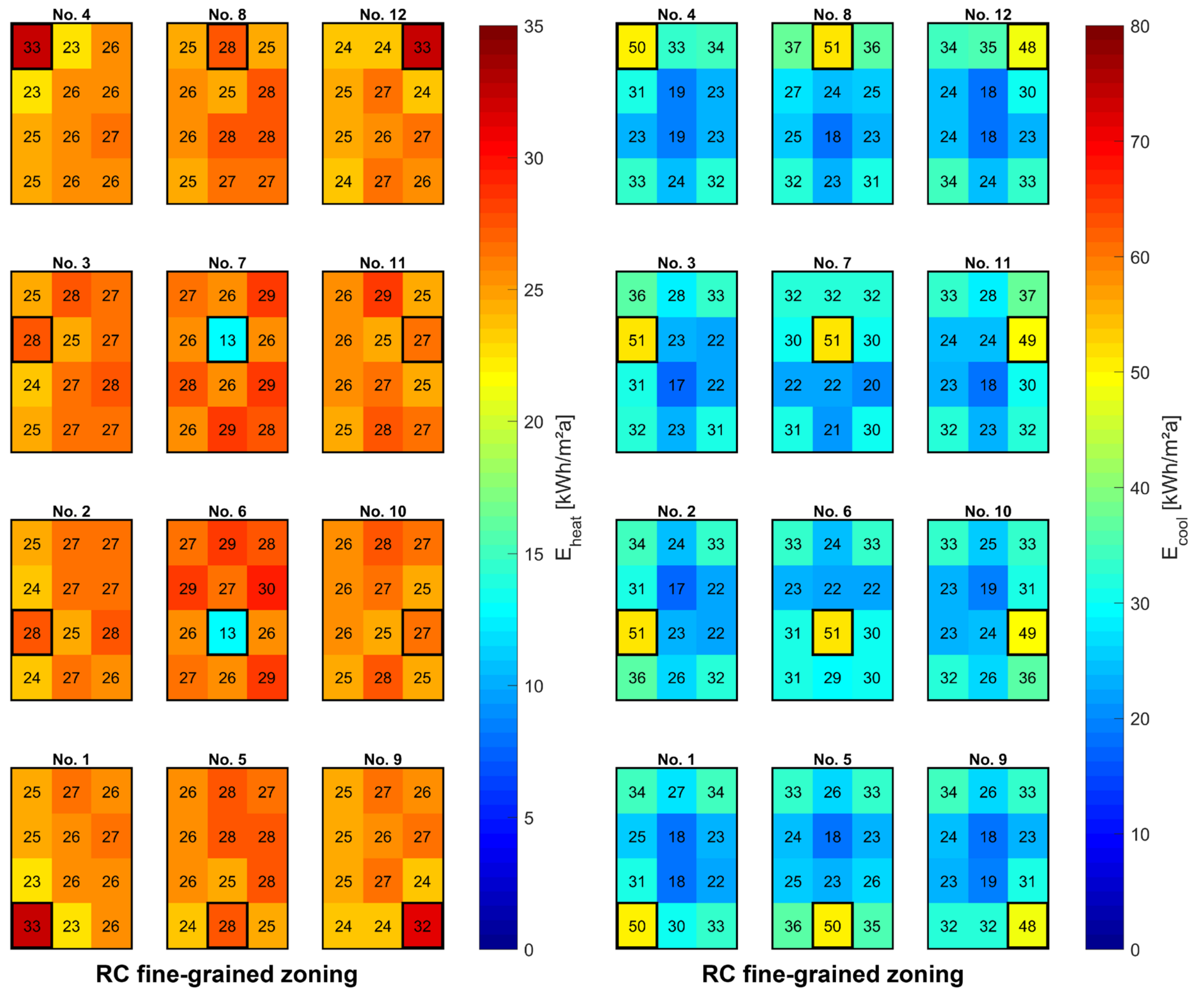


Figure 58. RC – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 for fine-grained zoning

For the meeting room the same behavior as described and explained for the variants with MV can be observed: The position of the meeting room has a significant influence on its heating energy demand, but no significant influence on its cooling energy demand.

For the open-plan office, the influence on heating and cooling energy demand depends on the control zoning strategy: A higher number of control zones lead to an increasing influence of the space layout design on heating and cooling energy demand. However, even for a fine-grained zoning, no significant influence of the space layout design on E_{heat} and the EUI (as illustrated in Appendix D) of the airnodes in the open-plan office can be observed. Only for the cooling energy demand, a small influence that follows the same behavior as described for MV can be observed. This can be seen Figure 58 (right side).

Flexibility of Space Layout Design

As a result, the space layout design is *fully flexible* with regard to the thermal comfort in the meeting room and open-plan office, but particular attention should be paid when the meeting room is located in the corner area of the floor.

5.3.3 TABS and Basic Mechanical Ventilation

Thermal Comfort

Figure 59 shows the CV for the space layout design variants no. 1–12 for TABS with three, two and one heating and cooling curve (HC). It should be noted that the HC do not influence the control zoning in the open-plan office, as described in section 4.3.5. Thus, no difference between the control zoning strategies for the open-plan office can be observed.

For the meeting room, it is clearly shown that its position has a significant influence on its thermal comfort, as also explained for the variants before. For the TABS with one HC (floor-based zoning) and two HC (room-based zoning), high CV occur when the meeting room is located in the core areas, because in these variants no separate HC is assumed for it. This is important, because if the meeting room is positioned in the core area, it is not influenced by the solar radiation and thus has different heating and cooling requirements. Furthermore, TABS have a high thermal inertia and thus cannot react immediately to changes of the solar radiation. Therefore, different HC are recommended for areas with different solar gains. The control zoning could be further improved if also a separate HC is assumed for each meeting room with a different façade direction.

When separate HC are applied in the core areas (3 HC room-based zoning), the highest CV are obtained in if the meeting room is position in the middle of the south façade, because here high solar gains occur. In all positions, most of the CV in the meeting room are due to overheating, because the TABS system cannot provide a high cooling power. However, the CV are still within the CV limit of 42 Kh/a.

For the open-plan office, only small variations in CV occur for the different space layout designs. This can also be explained with the high thermal inertia of the system and the operation time of 24 hours, which both allows all temperature fluctuations that occur during the day to be compensated. Thus, no significant temperature fluctuations or differences in individual areas occur, which in total leads to a homogeneous room climate in the open-plan office. The maximal range can be observed for airnode A4, which varies from 1–4 Kh/a. Moreover, all CV in the open-plan office are also due to overheating, because of the relatively low cooling power of the TABS.

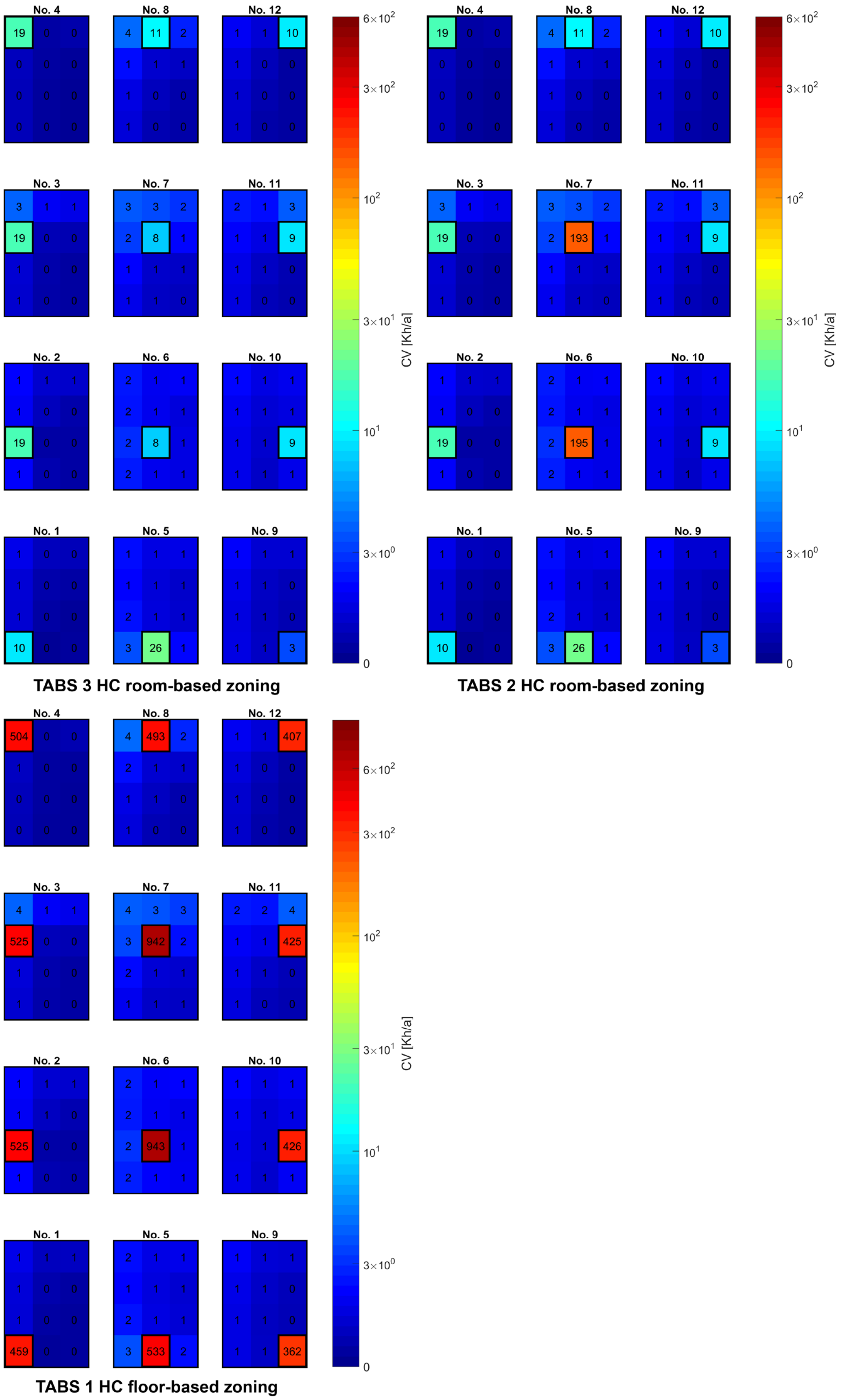


Figure 59. TABS – comparison of CV for space layout variants no. 1–12 for all control zoning strategies

Energy Demand

In Figure 60, the heating and cooling energy demand for the space layout design variants no. 1–12 for TABS with three HC are illustrated. In addition, the EUI for TABS with three and one HC is shown in Appendix D.

For the meeting room the same behavior as described and explained for the variants with MV and RC can be observed: The position of the meeting room has a significant influence on its heating energy demand, but no significant influence on its cooling energy demand. Moreover, it is clearly shown that the meeting room has a different heating and cooling energy demand if it is positioned in the core areas, which justifies the application of a third HC for these areas.

For the open-plan office, the space layout design has no significant influence on E_{cool}, E_{heat} and thus EUI (as illustrated in Appendix D) of the airnodes. As mentioned before, the high thermal inertia and the operation time of 24 hours lead to a homogenous distributed heating and cooling energy demand.

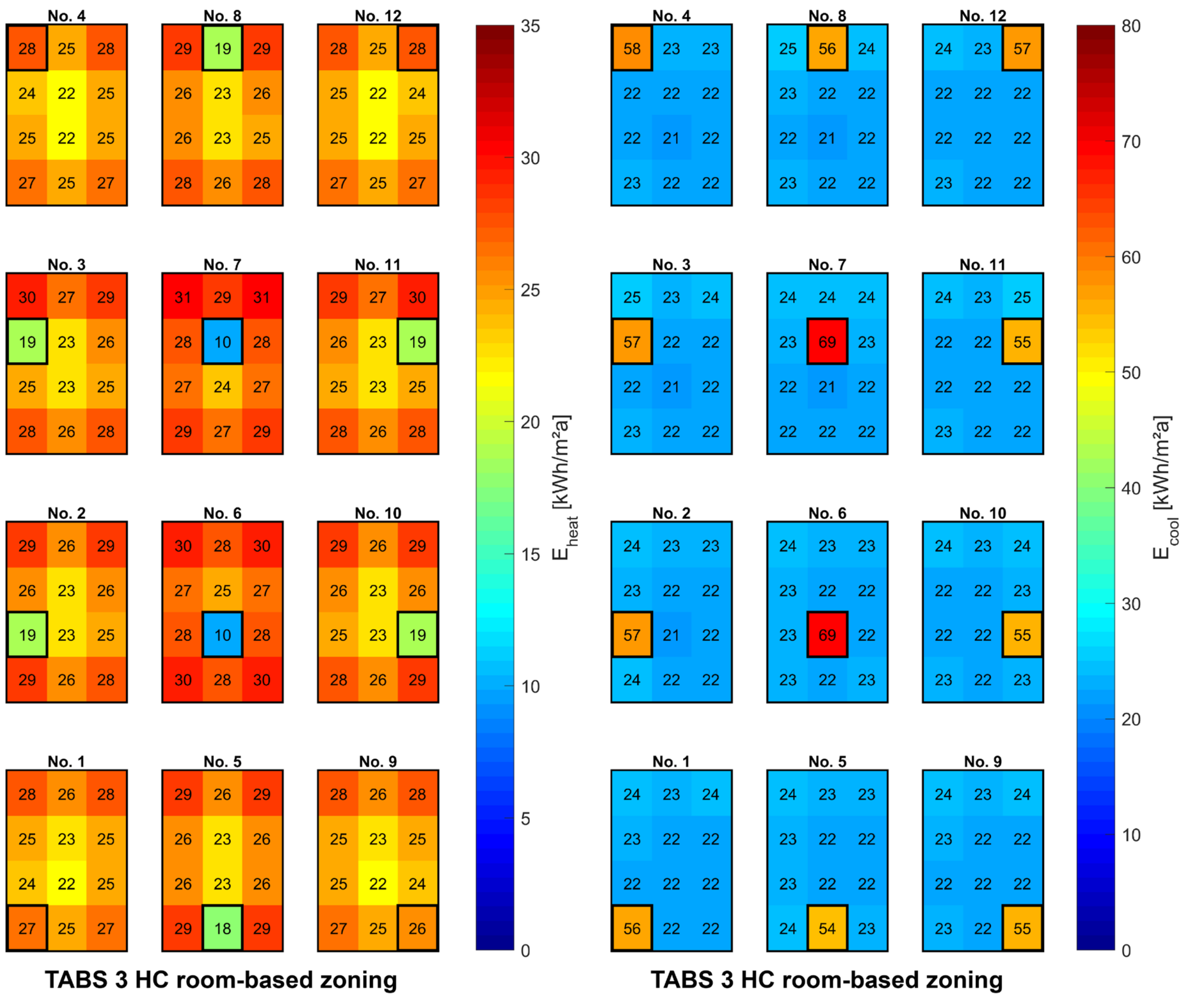


Figure 60. TABS – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 with 3 HC

Flexibility of Space Layout Design

As a result, the space layout design for buildings with TABS-based HVAC systems is *fully flexible* with regard to the thermal comfort in meeting room and open-plan office, but particular attention should be paid when the meeting room is located in the core area without separate HC.

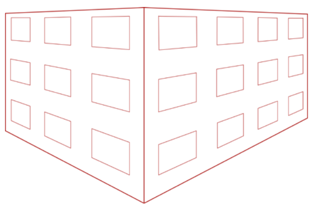
5.4 Recommendations for an "Office Space Design for Flexibility"

In this section, recommendations for the realization of an *office space design for flexibility* are presented. At this point, it is not possible to formulate general guidelines applicable to all buildings, as the design decision strongly depends on individual aspects of the office space such as construction parameters, location and usage of the rooms. Nevertheless, the approach to model and investigate an office space design for flexibility, described in section 4.1, can be transferred to other office spaces as well. Furthermore, the methodology presented can be used as a guideline for the evaluation of office spaces, presented in section 5.4.1. In the following, an explanation on how the results from this case study can be interpreted using the flex index and an assessment of the design scenarios and research questions, defined in section 1.2, are given.

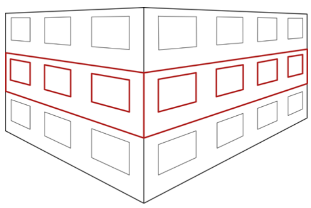
5.4.1 Evaluation Guidelines

To evaluate an office building and develop an office space design for flexibility, the steps presented in this section are recommended. These evaluation guidelines can be transferred to every office building that is built in a grid structure, as described in 2.1.2. Depending on the office type that should be realized in the office space, different space layout design variants should be assumed. An overview of the different office types is given in section 2.1.3. The case study presented in this work demonstrates the application of the approach for an open-plan office with a single meeting room.

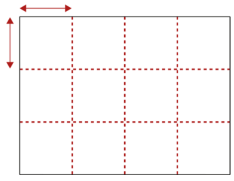
1) Select an **office building**, which is built in a grid structure



2) Select a **representative floor** with a usage and energy demand typical for most parts of the building. It should be noted that the ground and top floor could have different energy demands, due to the different boundary conditions.



3) Define the **grid size** according to the façade grid or possible room positions



4) Define the **global information** in the simulation model

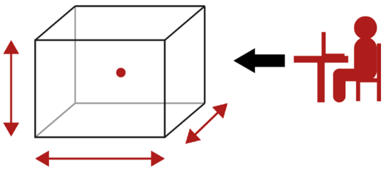
   4.1) Define the building construction parameters

   4.2) Select the weather data according to the location of the building

5) Define the **airnode-specific setup**

   5.1) Define the airnode size in simulation model according to the grid size

   5.2) Define all internal gains from people, equipment and lighting



6) Define the **flexible design parameters**

   6.1) Define all **space layout design** variants

   Define the size of the meeting room (the size should be a multiple of the airnode size)

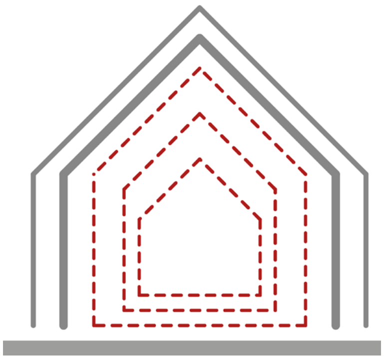
   6.2) Define the **HVAC system design** options

   Define a new HVAC system design or use the HVAC system design options from the case study including:

      6.2.1) HVAC system configuration

      6.2.2) Control zoning strategy

      6.2.3) Controlled variable

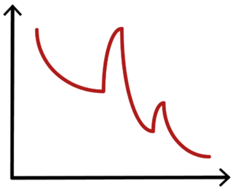


7) **Run thermal building simulations** for all variants

8) **Post-processing and evaluation of the results**

   8.1) Define evaluation criteria for thermal comfort, energy efficiency and flexibility

   8.2) Calculate the flex index for an holistic evaluation of different design questions



5.4.2 Flex Index

To support design decisions, a holistic view of the results of all variants can be useful. Thus, the so called “flex index” is introduced to summarize the resulting data and express it in one number. The *flex index* can be used to express a tendency for a design decision, depending on the specific design scenarios listed below.

For each variant, the resulting data are aggregated on a floor level to summarize the results for thermal comfort and energy demand for one variant. The flex index is calculated according to Equation (5-8) and (5-9) with the comfort violations (CV), the energy use intensity (EUI) and their standard deviations ($\sigma_{\mathrm{CV}}, \sigma_{\mathrm{EUI}}$) for the meeting room and the open-plan office. To define the flex index as a dimensionless quantity and scale the value for each variable to the same order of magnitude, each variable is divided by a reference value, as defined in Equation (5-10)–(5-17). The flex index ($flex_i$) is than calculated for each office space design configuration, with $i \in \{1, \dots, n\}$ being the index for the different configurations and n being the total number of configurations ($n, i \in \mathbb{N}$), as follows:

$$x_i = \left(\left(\frac{CV}{CV_{\mathrm{ref}}} + \frac{\sigma_{\mathrm{CV}}}{\sigma_{\mathrm{CV,ref}}} + \frac{EUI}{EUI_{\mathrm{ref}}} + \frac{\sigma_{\mathrm{EUI}}}{\sigma_{\mathrm{EUI,ref}}} \right)_{\mathrm{MR}} \cdot w_{\mathrm{MR}} + \left(\frac{\overline{CV}}{CV_{\mathrm{ref}}} + \frac{\overline{\sigma_{\mathrm{CV}}}}{\sigma_{\mathrm{CV,ref}}} + \frac{\overline{EUI}}{EUI_{\mathrm{ref}}} + \frac{\overline{\sigma_{\mathrm{EUI}}}}{\sigma_{\mathrm{EUI,ref}}} \right)_{\mathrm{office}} \cdot w_{\mathrm{office}} \right)_i \tag{5-8}$$

$$flex_i = 1 - \frac{x_i - \min\{x_i\}}{\max\{x_i\} - \min\{x_i\}} \quad with\ flex_i \in [0, \dots, 1] \tag{5-9}$$

with w_{MR} being the weighting factor for the meeting room, w_{office} being the weighting factor for the open-plan office. In Equation (5-9) the result of x_i is normalized to a range of 0–1 and the flex index is defined. Moreover, to calculate the values for the open-plan office, the mean value of the results of all airnodes located in it are used, with a total number of 11 airnodes. It should be noted that if more than one airnode is located in the meeting room, also the mean value of the results of all airnode in the meeting room should be used in the calculation.

The reference values for CV are defined according to the CV limits from DIN EN 15251 [26], as described in Equation (5-10) and (5-11). The reference values for EUI are defined according to the reference values for an office building with medium energy efficiency [96], as described in Equation (5-14) and (5-15). Here, the same values for SCOP and SEER are used as in the case study described in the section 5.1.2. Moreover, the reference values of the standard deviations are defined as 5 % of the reference values for CV and EUI, according to

Equation (5-12), (5-13), (5-16) and (5-17). This definition is in accordance with the evaluation criteria for robustness in section 5.1.3. It should be noted that the reference value influences the weighting of the individual parameter in the flex index.

$$CV_{\mathrm{ref,MR}} = CV_{\mathrm{limit,MR}} = 42\ \frac{\mathrm{Kh}}{\mathrm{a}} \tag{5-10}$$

$$CV_{\mathrm{ref,office}} = CV_{\mathrm{limit,office}} = 63\ \frac{\mathrm{Kh}}{\mathrm{a}} \tag{5-11}$$

$$\sigma_{\mathrm{CV,ref,MR}} = CV_{\mathrm{ref,MR}} \cdot 0.05 = 2.1\ \frac{\mathrm{Kh}}{\mathrm{a}} \tag{5-12}$$

$$\sigma_{\mathrm{CV,ref,office}} = CV_{\mathrm{ref,office}} \cdot 0.05 = 3.15\ \frac{\mathrm{Kh}}{\mathrm{a}} \tag{5-13}$$

$$EUI_{\mathrm{ref,MR}} = \frac{E_{\mathrm{ref,heat,MR}}}{SCOP} + \frac{E_{\mathrm{ref,cool,MR}}}{SEER} + E_{\mathrm{ref,elec,MR}} = 118\ \frac{\mathrm{kWh}}{\mathrm{m^2 \cdot a}} \tag{5-14}$$

$$EUI_{\mathrm{ref,office}} = \frac{E_{\mathrm{ref,heat,office}}}{SCOP} + \frac{E_{\mathrm{ref,cool,office}}}{SEER} + E_{\mathrm{ref,elec,office}} = 65\ \frac{\mathrm{kWh}}{\mathrm{m^2 \cdot a}} \tag{5-15}$$

$$\sigma_{\mathrm{EUI,ref,office}} = EUI_{\mathrm{ref,MR}} \cdot 0.05 = 5.9\ \frac{\mathrm{kWh}}{\mathrm{m^2 \cdot a}} \tag{5-16}$$

$$\sigma_{\mathrm{EUI,ref,office}} = EUI_{\mathrm{ref,office}} \cdot 0.05 = 3.25\ \frac{\mathrm{kWh}}{\mathrm{m^2 \cdot a}} \tag{5-17}$$

In this case study, the weighting factors take into account the meeting room and the open-plan office to the same extent. Thus, the weighting factor for the meeting room is 0.5 and the weighting factor for the open-plan office is 0.5. However, the weighting factors can be defined individually based on the requirements of the project. For instance, if the thermal comfort in the open-plan office is more important than the thermal comfort of the meeting room, the weighting factors can be adapted accordingly. Using this approach, an evaluation of the office space based on individual aspects is possible. However, it should be noted that the flex index as proposed here does not differentiate between CV_{hot} and CV_{cold}. Moreover, it only considers the total EUI and not the heating and cooling energy demand in each airnode.

Table 14 shows the results for the flex index with the data generated in the case study and equal consideration of the meeting room and the open-plan office ($w_{\mathrm{office}} = 0.5, w_{\mathrm{MR}} = 0.5$).

In addition, the results for the flex index if only the meeting room is considered ($w_{\mathrm{office}} = 0$, $w_{\mathrm{MR}} = 1$) and if only the open-plan office is considered ($w_{\mathrm{office}} = 1, w_{\mathrm{MR}} = 0$) are shown in Table 15 and Table 16.

Table 14. Flex index for each office space design configuration with w_{Office} =0.5 and w_{MR} = 0.5

HVAC System Configuration		MV				RC				TABS		
Control Zoning Startegy		FG	CP	NS	RB	FG	CP	NS	RB	3 HC	2 HC	1 HC
Space Layout Design	No. 1	0.428	0.434	0.426	0.409	0.939	0.939	0.941	0.942	0.999	0.725	0.103
	No. 2	0.439	0.445	0.437	0.420	0.942	0.942	0.944	0.945	0.997	0.723	0.089
	No. 3	0.438	0.444	0.436	0.420	0.942	0.942	0.943	0.945	0.997	0.723	0.089
	No. 4	0.388	0.394	0.386	0.369	0.929	0.930	0.931	0.932	0.997	0.723	0.094
	No. 5	0.468	0.474	0.466	0.450	0.943	0.943	0.945	0.946	0.995	0.721	0.088
	No. 6	0.414	0.466	0.457	0.396	0.943	0.944	0.945	0.946	0.999	0.685	0.000
	No. 7	0.414	0.465	0.457	0.395	0.943	0.944	0.945	0.946	0.999	0.685	0.000
	No. 8	0.442	0.448	0.440	0.424	0.942	0.942	0.944	0.945	0.998	0.724	0.096
	No. 9	0.449	0.454	0.446	0.430	0.942	0.942	0.944	0.945	1.000	0.726	0.124
	No. 10	0.460	0.466	0.458	0.442	0.943	0.943	0.945	0.946	0.999	0.725	0.111
	No. 11	0.460	0.465	0.457	0.441	0.943	0.943	0.945	0.946	0.999	0.725	0.111
	No. 12	0.409	0.415	0.405	0.390	0.938	0.938	0.939	0.940	0.998	0.724	0.115

The higher the value, the better are the results for thermal comfort and energy efficiency of the office space design configuration. Thus, a high flex index indicate a high flexibility. The columns show the different HVAC system designs, including the HVAC system configurations and control zoning strategies and the rows show the different space layout design variants. Moreover, the control zoning strategies are abbreviated as follows: fine-grained zoning (FG), core/perimeter zoning (CP), north/south zoning (NS) and room-based zoning (RB). For each HVAC system configuration, the colors indicate the variants with a high flex index and thus also high flexibility (marked in green) and the variants with a low flex index and thus also low flexibility (marked in red). As described before, for space layout design variant no. 1, no. 4, no. 9 and no. 12, the meeting room is located in a corner area of the floor, for the variant no. 6 and no. 7, it is located in a core area and for all other variants, it is located in a perimeter area.

Moreover, the arrows mark how this table can be used for design decisions, which are presented in the next section. The blue arrow indicates that the column is fixed and a variant in the row can be selected. Here, the HVAC system design, including the HVAC system configuration and the control zoning is fixed and a suitable space layout design needs to be selected. The red arrow indicates that the row is fixed and a variant in the column can be selected. Here, the space layout design variant is fixed and a suitable HVAC system design needs to be selected.

Table 15. Flex index for the meeting room for each office space design configuration

HVAC System Configuration		MV				RC				TABS		
Control Zoning Startegy		FG	CP	NS	RB	FG	CP	NS	RB	3 HC	2 HC	1 HC
Space Layout Design	No. 1	0.452	0.460	0.459	0.452	0.939	0.940	0.940	0.940	0.998	0.724	0.103
	No. 2	0.464	0.472	0.471	0.464	0.942	0.942	0.943	0.944	0.997	0.723	0.089
	No. 3	0.464	0.472	0.470	0.464	0.942	0.942	0.943	0.944	0.997	0.723	0.089
	No. 4	0.412	0.420	0.419	0.412	0.929	0.930	0.931	0.931	0.996	0.722	0.094
	No. 5	0.494	0.502	0.501	0.494	0.943	0.944	0.944	0.945	0.995	0.721	0.088
	No. 6	0.440	0.494	0.493	0.441	0.944	0.944	0.945	0.945	0.999	0.685	0.000
	No. 7	0.440	0.494	0.492	0.441	0.944	0.944	0.945	0.945	0.999	0.685	0.000
	No. 8	0.468	0.476	0.474	0.468	0.942	0.943	0.943	0.944	0.998	0.724	0.096
	No. 9	0.473	0.481	0.479	0.473	0.942	0.942	0.943	0.943	1.000	0.726	0.124
	No. 10	0.485	0.493	0.492	0.486	0.943	0.944	0.944	0.945	0.999	0.725	0.111
	No. 11	0.485	0.493	0.492	0.485	0.943	0.944	0.944	0.945	0.999	0.725	0.111
	No. 12	0.433	0.441	0.439	0.433	0.938	0.938	0.939	0.939	0.998	0.724	0.114

Table 16. Flex index for the open-plan office for each office space design configuration

HVAC System Configuration		MV				RC				TABS		
Control Zoning Startegy		**FG**	**CP**	**NS**	**RB**	**FG**	**CP**	**NS**	**RB**	**3 HC**	**2 HC**	**1 HC**
Space Layout Design	**No. 1**	0.454	0.406	0.259	0.050	0.972	0.966	0.989	1.000	0.975	0.975	0.968
	No. 2	0.426	0.385	0.242	0.036	0.969	0.963	0.986	0.997	0.973	0.973	0.967
	No. 3	0.428	0.375	0.236	0.030	0.969	0.963	0.986	0.997	0.973	0.973	0.966
	No. 4	0.460	0.412	0.267	0.061	0.972	0.965	0.988	1.000	0.975	0.975	0.969
	No. 5	0.414	0.365	0.223	0.020	0.969	0.963	0.985	0.997	0.971	0.971	0.964
	No. 6	0.418	0.371	0.215	0.008	0.965	0.958	0.981	0.992	0.969	0.970	0.963
	No. 7	0.411	0.363	0.203	0.000	0.965	0.958	0.981	0.992	0.969	0.969	0.962
	No. 8	0.419	0.367	0.226	0.027	0.969	0.963	0.986	0.997	0.972	0.972	0.966
	No. 9	0.447	0.395	0.255	0.048	0.971	0.965	0.989	1.000	0.974	0.974	0.967
	No. 10	0.431	0.382	0.241	0.031	0.969	0.963	0.986	0.997	0.972	0.972	0.966
	No. 11	0.425	0.380	0.236	0.026	0.969	0.963	0.986	0.997	0.972	0.972	0.965
	No. 12	0.456	0.408	0.230	0.056	0.971	0.965	0.988	1.000	0.975	0.974	0.968

5.4.3 Design Decisions

In order to make design decisions based on the office space design for flexibility approach, the previously introduced flex index can be used. In the following, the design scenarios defined in section 1.2 are evaluated based on the flex index for the data resulted from the case study described in this work. Table 17 summarizes how the flex index can be used to evaluate each design scenario. Moreover, an explanation for each design scenario is given below. It should be noted that the design decisions are based on the flex index results from Table 14, taking into account the meeting room and the open plan office to the same extent. The design decisions can be slightly different if other weighting factors are applied.

Table 17. Design decisions for design scenario no. 1–4

Design scenario	**Life cycle phase**	**(1) Space layout design**	**(2) HVAC system conf.**	**(3) Control zoning strategy**	**Design decisions**
No. 1	Conceptual design	Variable	Variable	Variable	Select the variant with the overall highest flex index
No. 2	Conceptual design	Variable	Fixed	Fixed	Fix the column and select the variant with the highest value in the row (marked with blue arrow)
No. 3	Operation/renovation	Variable	Fixed	Fixed	
No. 4	Operation/retrofitting (HVAC)	Fixed	Variable	Variable	Fix the row and select the variant with the highest value in the column (marked with red arrow)

Design Scenario No. 1

For design scenario no. 1, the variant with the highest flex index and thus highest flexibility of all office space design configurations should be selected. For the results of the case study, the variants with RC and TABS result in a higher flex index than the variants with MV.

In general, for variants with RC, the control zoning strategy and the space layout design has only a small influence on the flex index, as shown in Table 14. However, the variants with a room-based zoning result in slightly higher flex indexes than variants other zoning strategies. If only the meeting room is considered, as shown in Table 15, the space layout design no. 6 and no. 7, where the meeting room in located in the core area and space layout design no. 5, no. 10 and no. 11, are recommended for office spaces with RC, independent from the control zoning strategy.

For TABS, a control zoning based on three HC is recommended, but the space layout design has no significant influence on the result. Thus, this variant is recommended for an office space whose space layout design needs to be changed frequently.

In general, MV is only recommended with additional heating and cooling in the meeting room. If a MV system should be used and the meeting room is not considered in the flex index, as shown in Table 16, a fine-grained zoning is recommended.

Design Scenario No. 2 and 3

For design scenario no. 2 and no. 3, the HVAC system design, including the HVAC system configuration and the control zoning are fixed and a suitable space layout design needs to be selected. Thus, the column should be considered as fixed and the variant with the highest flex index in the row should be selected. This procedure is indicated with a blue arrow in Table 14, Table 15 and Table 16.

The results are different for each HVAC system design: For variants with MV, when fine-grained is applied, the highest flexibility is reached when the meeting room is located in the perimeter area (variants no. 5, no. 10 and no. 11). When core/perimeter or north/south zoning is applied, also high flex indexes are reached when the meeting room is located in the core area (variants no. 6 and no. 7). A room-based zoning is not recommended, as only low flex indexes are reached for all space layouts. For all variants with MV, the space layout design no. 4 and no. 12 (meeting room in the north/west and north/east corner) should be avoided, independent of the control zoning.

In general, for variants with RC, the space layout design is very flexible, because the flex index varies only slightly for the different variants. However, the space layout design no. 4 (meeting room in the north/west corner) should be avoided. It should be noted that if only the meeting room is considered, as shown in Table 15, the highest flex indexes are reached when the meeting room is located in the core area (variants no. 6 and no. 7), almost independent from the control zoning strategy. Moreover, high values are also reached when the meeting room is located in the perimeter area (variants no. 5, no. 10 and no. 11).

For variants with TABS, the flex index is almost independent from the space layout design when three HC are used. For variants with two and one HC the space layout designs no. 6 and no. 7 (meeting room in the core area) should be avoided. Moreover, for the variants with one HC, low flex indexes are reached for all space layout design variants. Overall, it can be said that space layout design with the meeting room located in the corner areas is only recommended for variants with TABS.

Design Scenario No. 4

For design scenario no. 4, the space layout design is fixed and a suitable HVAC system design needs to be selected. Thus, the row should be considered as fixed and the variant with the highest flex index in the column should be selected. This procedure is indicated with a red arrow in Table 14, Table 15 and Table 16.

For all space layout design variants, the highest flex index is reached with TABS with three HC. Apart from that, all other variants with RC are the second best choice for all space layout design variants. If only the meeting room is considered, as shown in Table 15, TABS with three HC are the best choice. In contrast, if only the open-plan office is considered, as shown in Table 16, an RC with room-based or north/south zoning should be selected.

If only MV variants are considered, the north/south zoning results in the highest flexibility. However, it should be noted that all flex indexes for variants with MV are lower than for the variants with RC or TABS, independent from the space layout design and control zoning strategy. Therefore, this MV system is not recommended if a flexible office space design should be achieved.

Applicability of the Flex Index

In summary, the flex index as presented here is an effective way of evaluating office space different design scenarios.

It is noted that, the flex index is defined in such a way that a value of one indicates an "absolute flexibility", i.e. the exact same values for thermal comfort and energy demand would be obtained independent of the office space design configuration. This situation is mainly a hypothetical one, not likely to be fulfilled in reality.

In addition, the calculated values for the index are based on the results for the office space design configurations for the office building in this case study and should therefore not to be used as absolute values for comparison with other buildings.

Furthermore, other studies could use different values for the weighting factors, reference values or slightly change the Equation (5-8) and (5-9) to investigate different aspects of the office space design. In spite of such modifications, the general methodology presented here, which can be described as reducing a large amount of data to a single index, is recommended to make decisions based on results from a large-scale parametric simulation study. In other words, the introduced flex index is a way to reduce complexity and to evaluate the data based on a user-defined weighting of the results.

5.5 Limitations

In this section, the limitations of the presented approach are discussed and possible improvements are listed. The section is divided into limitations resulting from model assumptions and limitations regarding the evaluation criteria of the results.

First of all, it should be mentioned that a generalization of the results from the case study is not possible, as the design decision strongly depends on individual aspects of the project.

Model Assumptions

In order to evaluate the office space on a detailed level, a high number of airnodes/zones are assumed. This assumption lead to a longer simulation time. Moreover, as mentioned in [69]: "The drawbacks of a high number of zones include greater computation intensiveness, as well as difficulties in creating, checking and modifying models, and interpreting simulation results". Nevertheless, some assumptions are made to simplify the building model. All assumptions and simplification regarding the calculations in thermal building simulation are listed in section 4.1.2. The boundary conditions and parameters assumed for the building model can be found in the descriptions of the case study in section 4.2.

Oher studies [97] have found that the occupant-related assumptions have a significant influence on design decisions. In this case study, the number of occupants and the occupancy schedule of the rooms are defined according to common standards and are equal for all variants. Thus, the influence of different occupancy-related assumptions has not been investigated in detail. However, a comparison between the assumptions for internal gains listed in common standards can be found in the Appendix B.

Since the case study focuses on thermal comfort, the HVAC system control is optimized to provide maximum thermal comfort in the office space, described in section 4.3. Accordingly, energy efficiency is only a secondary goal and further improvements can be made to the HVAC system control, such as a reduction in the operation hours for TABS.

Moreover, in the case study a speculative office building is simulated, which is modelled based on a typical modern office building. Real sampled data is not available for this building and thus the model is not validated.

Evaluation Criteria

To assess the simulation results, evaluation criteria such as thermal comfort, energy demand and robustness is used. The criteria are defined in section 5.1.

In order to calculate the EUI, it is assumed that the SCOP and SEER are defined as constants across all variants and thus are not calculated depending on the HVAC system and its operation temperature. Defining these values more precisely can result in higher differences between the EUI of the HVAC systems. Moreover, it should be considered that for systems that operate at different temperature levels, different energy sources could be used. For instance, for systems with a low supply temperature spread such as TABS, geothermal energy can directly be used for heating and cooling, also free cooling is possible. Whereas for mechanical ventilation systems, which have to realize a higher temperature spread, additional heat pumps and/or chillers may be required to heat and cool the supplied water.

For the evaluation of the thermal comfort, an adaptive approach is used to calculate the comfort violations (CV) in each airnodes. However, the indicator CV does not show differences between the variants when the operative temperature is within the defined comfort limits. Figure 61 shows the operative room temperature (T_{op}) depending on the ambient air temperature (T_{amb}) for all airnodes and space layout design variants with MV and RC with fine-grained zoning and TABS with three HC (room-based zoning). Comparing the results shows that RC results lie closer together than the results for MV and TABS, but are almost the same CV as TABS. This implies that a different indicator than CV is needed to evaluate results that lie within the comfort limits.

Moreover, to achieve a holistic evaluation of the office space design for flexibility, it could be useful to consider other aspects of the indoor environmental quality such as indoor air quality, visual and acoustic comfort into account. Moreover, this study does not consider economical aspects when choosing the HVAC system.

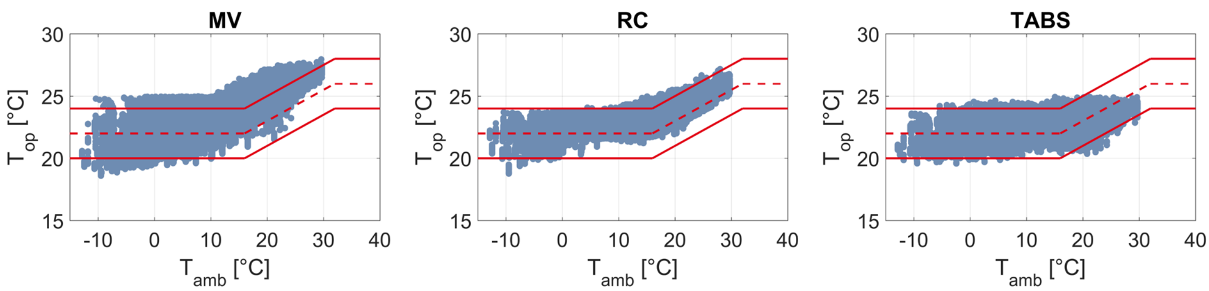


Figure 61. Comparison of the operative temperature (T_{op}) for variants with MV and RC with a fine-grained zoning and TABS with 3 HC (room-based zoning) as function of the ambient air temperature (T_{amb})

6 Conclusions and Outlook

6.1 Conclusions

This dissertation presented a novel approach to model and evaluate flexibility in office spaces and analyzed the influence of the space layout and HVAC system design on the thermal comfort, energy efficiency and flexibility of the office space. Moreover, recommendations for an *office space design for flexibility* were given to apply the approach and findings to other office buildings.

During an operation phase of an office building, the space layout design needs to be adapted frequently. Thus, in order to maintain an energy-efficient operation and high thermal comfort without requiring a large-scale retrofit, the HVAC system needs to be flexible. In this context, a *robust* HVAC system design will enable adjustments during the operation phase and the reactions to unpredictable events. As a result, the main challenge is to achieve both flexibility and high thermal comfort in an energy-efficient way. In the reviewed literature, the correlation between the space layout design and the HVAC system design to enable flexible office spaces has not been investigated in detail. Moreover, in this regard, no approach for decision making in different life cycle phases was found.

According to the main objective, this dissertation offers a *design for flexibility* approach that aims at creating robust solutions for office spaces. In addition, a comprehensive understanding of the correlation between the space layout design and the HVAC system design, including the HVAC system configuration and its control zoning strategy, enables design decisions in office spaces that consider thermal comfort, energy efficiency and flexibility.

The developed approach was implemented using parametric modeling and thermal building simulation and was then applied in a case study to a modern office building. In this context, three HVAC system configurations, which are commonly used in office buildings, were investigated with fourth different control zoning strategies and a flexible space layout design. Of special interest was to evaluate the influence of each of these *flexible* design parameters on thermal comfort and energy demand and to identify configurations of these flexible design parameters that provide robust solutions for office spaces. In the presented case study, the following HVAC system configurations are compared: a mechanical ventilation system (MV), radiant ceilings with a basic mechanical ventilation (RC) and a thermally-active building system with a basic mechanical ventilation (TABS). In summary, the variants with MV result in the highest energy demand, mainly due to the high electricity demand for the fans. The variants with RC and TABS are more energy-efficient solutions for the office space investigated in this dissertation.

Moreover, in the open-plan office, critical areas were identified to which particular attention should be paid in the design process. These areas tend to have higher comfort violations (CV) and are located in corners and/or are adjacent to the meeting room. In addition, if the meeting room is positioned in a corner and/or core area, this may have negative effects on its thermal comfort, depending on the HVAC system configuration. In general, almost all CV in the meeting room are due to overheating, because of the high internal loads during occupied times. Only variants with RC remain within the thermal comfort limit, thus for all other variants a secondary heating and cooling system is recommended in the meeting room.

In general, the MV is the most sensitive system, which becomes evident in the high standard deviations in thermal comfort and energy demand that are obtained for different space layout designs and areas in the office space. When the space layout design and control zoning change, not all airnodes remain within the comfort limit. To improve the thermal comfort, the focus should be on critical areas. In contrast, RC and TABS show a higher robustness, especially in terms of thermal comfort. For these variants, high thermal comfort can be achieved independently from space layout design and control zoning strategy, which enables a flexible office space.

The next sub-objective after the influence of the HVAC system configuration was to identify the influence of the control zoning strategies on thermal comfort and energy demand. The results show that the influence varies significantly depending on the HVAC system configuration. In general, the following applies to all airnodes located in the open-plan office: If the number of control zones decreases (from fine-grained to room-based zoning) the comfort violations increase and the energy demand decreases for the individual areas of the office space. For the variants with MV, a zoning strategy with a high number of control zones (fine-grained or core/perimeter zoning) is recommended to avoid high comfort violations, especially in critical areas. In contrast, the control zoning strategy does not have a significant influence on the thermal comfort for variants with RC or TABS. Small effects can only be observed for corner areas and/or areas with an adjacent meeting room. Moreover, to avoid high CV for variants with TABS, a different heating and cooling curve (HC) should be applied for meeting rooms positioned in the core areas, compared to meeting rooms positioned in the perimeter areas of the office space.

The next sub-objective was to identify the influence of the space layout design on the above-mentioned evaluation criteria. As stated previously, in office buildings, the space layout usually needs to be repeatedly redesigned in order to meet tenants' requirements during the operation phase. For all HVAC system configurations, the meeting room position has a significant influence on its thermal comfort and energy demand and thus its flexibility is limited. For variants with MV, the influence of the space layout design on thermal comfort in the open-plan office increases when the number of control zones decreases. Thus, for control zoning strategies with few zones, such as north/south or room-based zoning, high CV occur in critical areas. Thus, for the open-plan office, the space layout design is flexible if an appropriate number of control zones is implemented. For variants with RC and TABS, the space layout design is fully flexible, because it has no significant influence on the CV and energy use intensity (EUI), independent from the control zoning strategy. However, particular attention should be paid when the meeting room is located in critical areas.

In conclusion, the results from this case study indicate that RC and TABS are more promising solutions for flexible office spaces compared to MV to keep the operative temperature in the room within the thermal comfort limits. Moreover, the approach presented in this dissertation has been shown to be an effective way of investigating flexibility in office buildings.

Another sub-objective consisted of giving recommendations for an *office space design for flexibility*, to be able to transfer the knowledge to other office spaces and to evaluate design scenarios. Here, guidelines for the evaluation of an office space were presented. Moreover, design decisions for different scenarios and life cycle phases of an office building were made based on the introduced *flex index* and the results from the case study. The approach is presented in general terms and can thus be transferred to other office spaces, enabling the design of flexible office spaces that guarantee high thermal comfort and an energy-efficient operation, robustly.

In summary, the presented results generally confirm the research hypothesis that *to design an office space for flexibility, three design parameters cannot be considered independently: space layout design, HVAC system configuration and control zoning strategy*. However, depending on the selected variants of the flexible design parameters, the others are more or less important to consider in the design decisions. For instance, for variants with MV, both the control zoning strategy and the space layout design are important to consider, whereas for variants with RC the control zoning strategy is less relevant. Moreover, the part of the hypothesis, which stated that *certain configurations of the design parameters can guarantee thermal comfort and an energy-efficient operation, even in the event of variations within the office space design,* could be completely confirmed with the results of the presented case study. Moreover, it was shown that the concept of office space design for flexibility describes an effective procedure of selecting robust configurations of flexible design parameters and that it can be transferred to other office spaces, too.

6.2 Outlook

In order for the office space design for flexibility approach to find its way into practice, the integration of this method into the building design process has been investigated in [49]. Here, a digital design workflow between Autodesk Revit [98] and Rhinoceros/Grasshopper [47, 48], where the TRNLizard Plugin [46] is used for the implementation of the presented approach, was realized. This workflow enables the designer to use the geometry and attributes defined within a building information model (BIM), to be automatically transferred to the thermal building simulation setup.

In a further step, the recommendations and results generated with this approach could automatically be integrated as boundary conditions in a BIM, to support designers without running a simulation in the foreground. Furthermore, the presented approach could be integrated in existing tools or approaches, whose aims are an automatic generation of HVAC system layouts [99], an automatic generation of space layout designs [100, 101] or an optimized spatial and thermal zoning [102].

Furthermore, as the recommendations for an office space design for flexibility can in principle be transferred to other buildings, it might be interesting to perform case studies with office buildings in other climate zones, with different shapes, different HVAC system designs, and/or other space usages. This could contribute to further explore the potential of an office space design for flexibility.

Moreover, the presented approach is considered as a fundamental step towards increased thermal comfort in flexible office spaces. Future research could evaluate the extent to which optimal model-based control approaches can compensate non-suitable control zoning or space layout design, and compare it to the control performance when the office space has been designed with flexibility in mind.

In addition, as described in [103], personal comfort systems can be used to condition the office space on a personal level. These systems are controlled based on personal comfort models, which are developed with data from the occupants to predict their individual thermal comfort requirements. Integrating these personal comfort models in the indoor environmental control for office spaces can improve energy efficiency and the occupant's satisfaction with the thermal environment. Future research could evaluate the potentials for combining these personal comfort models with the approach presented in this work, to design flexible office spaces, which offer a basic level of thermal comfort and address individual preferences of occupants with personal comfort systems.

In general, for future office buildings, a flexible use during the operation phase is increasingly important. In an interview, Norman Foster even emphasized that future office spaces must be flexible [104]: "They must be thoughtfully designed to adapt to the ways humans and society will inevitably change, and that requires more than just building open-plan layouts. […] Ultimately, the most enduring workplaces will take into account the deep-rooted desires of the people who spend time there." In conclusion, this dissertation does enable a flexible office space design with the aim to design such an enduring workspace that can guarantee high thermal comfort for the occupants and at the same time an energy-efficient operation. However, some interesting research questions remain open and thus further research in this field is recommended to create sustainable solutions for office spaces in the future.

References

[1] Klepeis *et al.*, "The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants," *Journal of Exposure Analysis and Environmental Epidemiology,* vol. 11, no. 3, pp. 231-252, 2001.

[2] Pérez-Lombard, Ortiz, and Pout, "A review on buildings energy consumption information," *Energy and Buildings,* vol. 40, no. 3, pp. 394-398, 2008.

[3] International Energy Agency and the United Nations Environment Programme, "2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector," 2018.

[4] International Energy Agency (IEA), "Transition to sustainable buildings: Strategies and opportunities to 2050," OECD/IEA, Paris, 2013.

[5] Zou, Xu, Sanjayan, and Wang, "Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives," *Energy and Buildings,* vol. 178, pp. 165-181, 2018.

[6] Brand, *How buildings learn*. Harmondsworth: Penguin Books, 1995, p. 243.

[7] Neufert and Kister, *Bauentwurfslehre*, 41 ed. Wiesbaden: Springer Vieweg, 2016, p. 594.

[8] Bielefeld, *Basics Office Design*. Basel: Birkhäuser, 2018, p. 70.

[9] Borrmann, König, and Koch, *Building information modeling*. Cham: Springer, 2018.

[10] Atkin and Brooks, *Total Facility Management*. Chichester, West Sussex, United Kingdom: Wiley-Blackwell, 2015.

[11] Duffy, "Measuring building performance," *Facilities,* vol. 8, no. 5, pp. 17-20, 1990.

[12] Baurmann and Reichel, *Support, Materialise: Columns, Walls, Floors*. Basel: Birkhäuser, 2014, p. 175.

[13] *Technischen Regeln für Arbeitsstätten (ASR), A1.2 Raumabmessungen und Bewegungsflächen*, 2013.

[14] Hausladen and Tichelmann, *Ausbau-Atlas*. Basel: Birkhäuser, 2009, p. 288.

[15] Wagner, Höfker, Lützkendorf, Moosmann, Schakib-Ekbatan, and Schweiker, *Nutzerzufriedenheit in Bürogebäuden, Empfehlungen aus Planung und Betrieb*. Stuttgart: FIZ Karlsruhe, Fraunhofer IRB Verlag, EnOB, 2015, p. 221.

[16] *ANSI/ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy*, ASHRAE, Atlanta, GA, 2010.

[17] Butera, "Chapter 3—Principles of thermal comfort," *Renewable and Sustainable Energy Reviews,* vol. 2, pp. 39-66, 1998.

[18] Kalz and Pfafferott, *Thermal Comfort and Energy-Efficient Cooling of Nonresidential Buildings*. Cham: Springer, 2014, p. 128.

[19] del Mar Castilla, *Comfort Control in Buildings*. London: Springer, 2014, p. 237.

[20] Jendritzky, Menz, Schirmer, and Schmidt-Kessen, "Methodik zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima-Michel-Modell)," in "Beiträge d. Akad. f. Raumforschung und Landesplanung," Hannover, 1990, vol. 114.

[21] *VDI 3787-2008:2, Environmental meteorology, Methods for the human biometeorological evaluation of climate and air quality for urban and regional planning at regional level, Part I: Climate*, 2008.

[22] Höppe, "Heat balance modelling," *Experientia,* vol. 49, no. 9, pp. 741-746, 1993.

[23] ASHRAE, *2017 ASHRAE Handbook. Fundamentals.* Atlanta, GA: ASHRAE, 2017.

[24] *EN ISO 7730:2005, Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*, Switzerland, 2005.

[25] Fanger, *Thermal comfort: Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Pr., 1970, p. 244.

[26] *DIN EN 15251: 2012-12, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; German version EN 15251:2007*, 2012.

[27] de Dear and Brager, "Developing an Adaptive Model of Thermal Comfort and Preference," in "ASHRAE Transactions," 1997, vol. 104.

[28] McCartney and Nicol, "Developing an adaptive control algorithm for Europe," *Energy and Buildings,* vol. 34, pp. 623-635, 2002.

[29] Clarke, *Energy simulation in building design*, 2 ed. Oxford: Butterworth-Heinemann, 2001, p. 362.

[30] Hensen and Lamberts, *Building performance simulation for design and operation*. London [u.a.]: Spon Pr., Taylor & Francis, 2011, p. 507.

[31] Oldewurtel *et al.*, "Use of model predictive control and weather forecasts for energy efficient building climate control," *Energy and Buildings,* vol. 45, pp. 15-27, 2012.

[32] Spitler, "Thermal load and energy performance prediction," in *Building performance simulation for design and operation*. London [u.a.]: Spon Pr., Taylor & Francis, 2011, p. 507.

[33] *ANSI/ASHRAE/IES 90.1-2016 Energy Standard for Buildings Except Low-Rise Residential Buildings*, ASHRAE, Atlanta, GA, 2016.

[34] COMNET, "Commercial Buildings Energy Modeling Guidelines and Procedures," Commercial Energy Services Network, 2010.

[35] Shin and Haberl, "Thermal zoning for building HVAC design and energy simulation: A literature review," *Energy and Buildings,* vol. 203, p. 109429, 2019.

[36] Baehr and Kabelac, *Thermodynamik*. Berlin [u.a.]: Springer, 2009, p. 667.

[37] *DIN V 18599-1:2018-09, Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 1: General balancing procedures, terms and definitions, zoning and evaluation of energy sources*, 2018.

[38] Klein and et al., "TRNSYS 18: A Transient System Simulation Program," Solar Energy Laboratory, University of Wisconsin, USA, http:// sel.me.wisc.edu/trnsys, 2017.

[39] Solar Energy Laboratory, Transsolar, CSTB, and TESS, "Trnsys 18 - Multizone Building modeling with Type56 and TRNBuild," University of Wisconsin, Madison, USA, 2017, vol. 5.

[40] Gebhart, "Surface Temperatur Calculations in Radiant Surroundings of Arbitrary Complexity – for Gray, Diffuse Radiation," *Internatinal Journal Heat Mass Transfer,* vol. 3, pp. 341-346, 1961.

[41] Gebhart, "Heat transfer," 2 ed. New York: McGraw-Hill, 1971, pp. 150-163.

[42] Transsolar. "TRNSYS - Type 336 Manual." (accessed 30.10.2019, 2019).

[43] *DIN EN 14240:2004-04, Ventilation for buildings - Chilled ceilings - Testing and rating*, 2004.

[44] Solar Energy Laboratory, Transsolar, CSTB, and TESS, "Trnsys 18 - Mathematical Reference," University of Wisconsin, Madison, USA, 2018, vol. 4.

[45] Glück, *Strahlungsheizung - Theorie und Praxis*. Karlsruhe: Müller, 1982, p. 507.

[46] Frenzel and Hiller, "TRNSYSLIZARD - Open source tool für Rhinoceros - Grasshopper zur einfachen, schnellen und sicheren Simulation einer Gebäudezone unter Ankopplung von TRNSYS und DAYSIM," in *BauSIM 2014 - 5th German-Austrian IBPSA Conference*, Aachen, Germany, 2014, pp. 490-496,

[47] Davidson. Grasshopper (V0.9.0076)

[48] Robert McNeel & Associates. Rhinoceros (V5.4)

[49] Gehl, "Erstellung von parametrischen Gebäudemodellen aus Building Information Modeling zur thermischen Gebäudesimulation," Master Thesis, Institut für Energietechnik, Fachgebiet Gebäudeenergiesysteme, Hermann-Rietschel-Institut, Technische Universität Berlin, Berlin, 2019.

[50] Lucas, Taylor, Miller, and Pratt, "Characterization of changes in commercial building structure, equipment, and occupants: End-Use Load and Consumer Assessment Program," Pacific Northwest Lab., Richland, USA, 1990.

[51] Fernandez, "Design for change: Part 1: diversified lifetimes," *Architectural Research Quarterly,* vol. 7, no. 2, pp. 169-182, 2003.

[52] Cole and Kernan, "Life-cycle energy use in office buildings," *Building and Environment,* vol. 31, no. 4, pp. 307-317, 1996.

[53] Saari, Tissari, Valkama, and Seppänen, "The effect of a redesigned floor plan, occupant density and the quality of indoor climate on the cost of space, productivity and sick leave in an office building–A case study," *Building and Environment,* vol. 41, no. 12, pp. 1961-1972, 2006.

[54] Musau and Steemers, "Space Planning and Energy Efficiency in Office Buildings: The Role of Spatial and Temporal Diversity," *Architectural Science Review,* vol. 51, no. 2, pp. 133-145, 2008.

[55] Shahzad, Brennan, Theodossopoulos, Hughes, and Calautit, "Energy and comfort in contemporary open plan and traditional personal offices," *Applied Energy,* vol. 185, pp. 1542-1555, 2017.

[56] Gratia and De Herde, "Design of low energy office buildings," *Energy and Buildings,* vol. 35, no. 5, pp. 473-491, 2003.

[57] Enders, Franke, Sen Dong, and Neubert, "Parameters to Design Low-Tech Strategies," in *PowerSkin 2019*, München, 2019: TU Delft, pp. 285-296,

[58] Dogan, Saratsis, and Reinhart, "The Optimization Potential of Floor-Plan Typologies in early Design Energy Modeling," in *BS 2015 - 14th Internatinal IBPSA Conference*, Hyderabad, India, 2015, Hyderabad, India, pp. 1853-1860,

[59] DGNB GmbH, "Economic quality, ECO2.1, Flexibility and adaptability," in "DGNB system – New buildings criteria set," 2018.

[60] Dogan, Reinhart, and Michalatos, "Autozoner: an algorithm for automatic thermal zoning of buildings with unknown interior space definitions," *Journal of Building Performance Simulation,* vol. 9, no. 2, pp. 176-189, 2016.

[61] Al horr, Arif, Katafygiotou, Mazroei, Kaushik, and Elsarrag, "Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature," *International Journal of Sustainable Built Environment,* vol. 5, pp. 1-11, 2016.

[62] Seppanen, Fisk, and Faulkner, "Cost benefit analysis of the night-time ventilative cooling in office building," in *Healthy buildings 2003, ISIAQ seventh international conference*, Singapore, 2003, vol. 3, pp. 394–399,

[63] Milton, Glencross, and Walters, "Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints," *Indoor Air 2000,* vol. 10, no. 4, pp. 211-221, 2000.

[64] Dascalaki and Santamouris, "On the potential of retrofitting scenarios for offices," *Building and Environment,* vol. 37, no. 6, pp. 557-567, 2002.

[65] Olesen and Mattarolo, "Thermal comfort and energy performance of hydronic radiant cooling systems compared to convective systems," in *HB 09 - 9th Internatinal Conference and Exhibition on Healthy Buildings*, Syracuse, New York, USA, 2009, pp. 1699-1702,

[66] Talami and Jakubiec, "Sensitivity of design parameters on energy, system and comfort performances for radiant cooled office buildings in the tropics," in *BS 2019 - 16th Internatinal IBPSA Conference*, Rome, Italy, 2019,

[67] Korolija, Marjanovic-Halburd, Zhang, and Hanby, "Influence of building parameters and HVAC systems coupling on building energy performance," *Energy and Buildings,* vol. 43, no. 6, pp. 1247-1253, 2011.

[68] Grondzik and Kwok, *Mechanical and Electrical Equipment for Buildings*. Newark, United States: John Wiley & Sons, Incorporated, 2019.

[69] Bres, Judex, Suter, and De Wilde, "Impact of zoning strategies for building performance simulation," in *EG-ICE 2017 - 24th International Workshop on Intelligent Computing in Engineering*, Nottingham, UK, 2017, vol. 14, pp. 35-44,

[70] Lipczynska, Kaczmarczyk, and Melikov, "Thermal environment and air quality in office with personalized ventilation combined with chilled ceiling," *Building and Environment,* vol. 92, pp. 603-614, 2015.

[71] Wang, Olesen, and Kazanci, "Using thermostats for indoor climate control in offices: The effect on thermal comfort and heating/cooling energy use," *Energy and Buildings,* vol. 188-189, pp. 71-83, 2019.

[72] Nagarathinam, Doddi, Vasan, Sarangan, Ramakrishna P., and Sivasubramaniam, "Energy efficient thermal comfort in open-plan office buildings," *Energy and Buildings,* vol. 139, pp. 476-486, 2017.

[73] Aryal and Becerik-Gerber, "Energy consequences of Comfort-driven temperature setpoints in office buildings," *Energy and Buildings,* vol. 177, pp. 33-46, 2018.

[74] Wang, Chen, Huang, and Lu, "Energy efficient HVAC control for an IPS-enabled large space in commercial buildings through dynamic spatial occupancy distribution," *Applied Energy,* vol. 207, pp. 305-323, 2017.

[75] De Wilde and Tian, "Predicting the performance of an office under climate change: A study of metrics, sensitivity and zonal resolution," *Energy and Buildings,* vol. 42, pp. 1674-1684, 2010.

[76] Georgescu and Mezić, "Building energy modeling: A systematic approach to zoning and model reduction using Koopman Mode Analysis," *Energy and Buildings,* vol. 86, pp. 794-802, 2015.

[77] Shin, "Development of a Procedure for Automating Thermal Zoning for Building Energy Simulation," Doctoral dissertation, Texas A & M University, 2018.

[78] Bleil De Souza and Alsaadani, "Thermal zoning in speculative office buildings: discussing the connection between space layout and inside temperature control," in *BSO 2014 - 1st Building Simulation and Optimisation Conference*, Loughborough, UK, 2012, pp. 417-424,

[79] Jiangshan, Yue, Xing, Xing, and Xin, "Impact of Model Simplification at Geometric Modelling Stage on Energy for Office Building," in *4th Building Simulation and Optimization Conference*, Cambridge, UK, 2018, pp. 402-406,

[80] O'Brien, Athienitis, and Kesik, "Thermal zoning and interzonal airflow in the design and simulation of solar houses: a sensitivity analysis," *Journal of Building Performance Simulation,* vol. 4, no. 3, pp. 239-256, 2011.

[81] Gärtner, Massa Gray, and Auer, "Flexible Office Buildings - The Effect of Space Layout Design and Zoning Strategies on Thermal Comfort and Energy Demand," in *BauSIM 2018 - 7th German-Austrian IBPSA Conference*, Karlsruhe, Germany, 2018, pp. 447-454,

[82] Gärtner, Massa Gray, and Auer, "Assessment of the impact of HVAC system configuration and control zoning on thermal comfort and energy efficiency in flexible office spaces," *Energy and Buildings,* vol. 212, p. 109785, 2020.

[83] The MathWorks Inc. MATLAB (R2016a)

[84] Meteotest AG. *Meteornom weather data Stuttgart (107370)*, TRNSYS 18,

[85] Robert Bosch GmbH, "Bosch Typisiertes Bauen Band 2 - Bürogebäude," 2014.

[86] *VDI 2067 Blatt 10:2013-09, Economic efficiency of building installations - Energy demand for heating, cooling, humidification and dehuminification*, 2013.

[87] *EnEV 2014, Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden*, 2014.

[88] *DIN V 18599-10:2018-09, Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 10: Boundary conditions of use, climatic data*, 2018.

[89] Melikov, Hanzawa, and Fanger, "Airflow characteristics in the occupied zone of heated spaces without mechanical ventilation," ASHRAE, 1988, vol. 94.

[90] Kovanen, Seppanen, Siren, and Majanen, "Turbulent air flow mesasurements in ventilated spaces," *Environmental Internatinal,* vol. 15, pp. 621-626, 1989.

[91] *DIN EN 13779:2007, Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems; German version EN 13779:2007*, 2007.

[92] Schmidt and Beck, "Prüfbericht über die Ermittlung der Kühlleistung einer Raumkühlfläche nach DIN EN 14240, Zent-Frenger GmbH, Typ VARICOOL spectra M," Prüfstelle Heizung-Lüftung-Klimatechnik Stuttgart, 2012.

[93] Zent-Frenger GmbH, "Gebäudetemperierung Energiebereitstellung," in "Technischer Gesamtkatalog," 2018.

[94] Tödtli, Gwerder, Lehmann, Renggli, and Dorer, *TABS Control: Steuerung und Regelung von thermoaktiven Bauteilsystemen ; Handbuch für Planung, Auslegung und Betrieb* Zürich: Faktor Verlag AG, 2009, p. 190.

[95] *Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products,* L 285, 2009.

[96] Bundesinstitut für Bau- Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR), "Vergleichswerte für den Energieverbrauch von Nichtwohngebäuden," in "BBSR-Online-Publikation Nr. 20/2019," Bonn, 2019.

[97] Abuimara, Gunay, and O'Brien, "Simulating the Impact of Occupants on Office Building Design: A Case Study," in *BS 2019 - 16th Internatinal IPBSA Conference*, Rome, Italy, 2019,

[98] Autodesk Inc. Revit (2019)

[99] Bres, Judex, Suter, and de Wilde, "A Method for Automated Generation of HVAC Distribution Subsystems for Building Performance Simulation," in *BS 2017 - 15th IBPSA Conference*, San Francisco, USA, 2017, pp. 1833-1842,

[100] Rodrigues, Gaspar, and Gomes, "Automated approach for design generation and thermal assessment of alternative floor plans," *Energy and Buildings,* vol. 81, pp. 170-181, 2014.

[101] Rodrigues, Gaspar, and Gomes, "Improving thermal performance of automatically generated floor plans using a geometric variable sequential optimization procedure," *Applied Energy,* vol. 132, pp. 200-215, 2014.

[102] Yi, "User-driven automation for optimal thermal-zone layout during space programming phases," *Architectural Science Review,* vol. 59, no. 4, pp. 279-306, 2016.

[103] Kim, Schiavon, and Brager, "Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control," *Building and Environment,* vol. 132, pp. 114-124, 2018.

[104] Stinson. "Apple's Architect Says the Future of Offices Must Be Flexible." (accessed 17.02.2019, 2019).

[105] *E DIN EN 16798-1:2015-07, Energy performance of buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6; German and English version prEN 16798-1:2015*, 2015.

[106] *SIA 2024, Raumnutzungsdaten für die Energie- und Gebäudetechnik*, Zürich, 2015.

Glossary

Controlled Variable

The controlled variable is used to control the HVAC system.

Control Zone

A control zone (also known as HVAC zone) refers to the space in a building, whose indoor climate is conditioned by the same HVAC system.

Control Zoning Strategy

The control zoning strategy defines how a space is divided into control zones. This includes the size, number and position of control zones.

Flexible Design Parameter

All parameters in the parametric building model, which can be changed between the different variants.

HVAC System Configuration

The HVAC system configuration defines only the components of system, without their control zoning and the controlled variable.

HVAC System Design

The HVAC system design defines all parameter of an HVAC system, which includes the HVAC system configuration, the control zoning strategy and the controlled variable.

Office Space Design

The office space design includes the space layout and HVAC system design, but also all building construction elements such as windows and walls. In total, it defines the design of a complete office space.

Office Space Design Configuration

A complete office space design configuration is defined if one option for each flexible design parameter is selected. This includes one space layout design, one HVAC system configuration, one control zoning strategy and a controlled variable.

Office Space Design for Flexibility

The concept of an office space design for flexibility describes the procedure of selecting robust configurations of design parameters for an office space. Moreover, this term is used for comfortable, energy-efficient indoor environments that are robust to changes in the office space design.

Robustness

Robustness is the ability of a system to maintain its current state, independent from disturbances and changes within the system. In this work, an HVAC system design is called *robust* if it can guarantee thermal comfort and an energy-efficient operation, even when changing the space layout design or its control zoning strategy.

Space Layout Design

The space layout design defines the location of rooms and interior drywalls in the floor plan.

Thermal Zone

Thermal zones separate the space within the building into smaller areas and are used to calculate the respective energy demand and thermal behavior of these areas. Within a thermal zone, the properties of the space are assumed to be homogeneous.

Workspace

Each employee has its own workplace, which includes the technical equipment and the furniture.

Appendix A

Study on Shading Control

In the following, the influence of different shading options and control strategies on solar gains, thermal comfort and their spatial distribution in the office space is investigated. For this study, the building model from the case study, described in section 4.2.2, and an ideal heating and cooling system (IHC) and with a room-based zoning, described in section 4.3.2, are used.

All variants with a shading device have an automatically operated external shading device with a shading fraction of 75 %. The different shading options and control strategies are defined as follows:

(S1)	**No shading**	No shading device is installed.
(S2)	**Closed shading**	The external shading device is always closed.
(S3)	**Radiation-based shading control**	The external shading is controlled by an hysteresis, which activates the shading when the solar radiation on the façade exceeds 200 W/m^2 [86] and deactivates it when the radiation falls below 150 W/m^2.
(S4)	**Temperature-based shading control**	The external shading is controlled as in the radiation-based shading control (S3) and has an additional temperature-based control, which operates as follows: If the air temperature in the airnode is above the cooling set point, defined in Equation (4-1)–(4-3), the shading is always closed, independent from the solar radiation.

In summary, the aim is to have a shading control that allows enough daylight to enter the office space and at the same time prevent the airnode from overheating due to high solar gains. As the radiation-based shading control (S3) is recommended in German strandards [86], this variant is used in the case study presented in sections 4.2–4.2.5. In the following, the results for all shading options and control strategies are presented in detail.

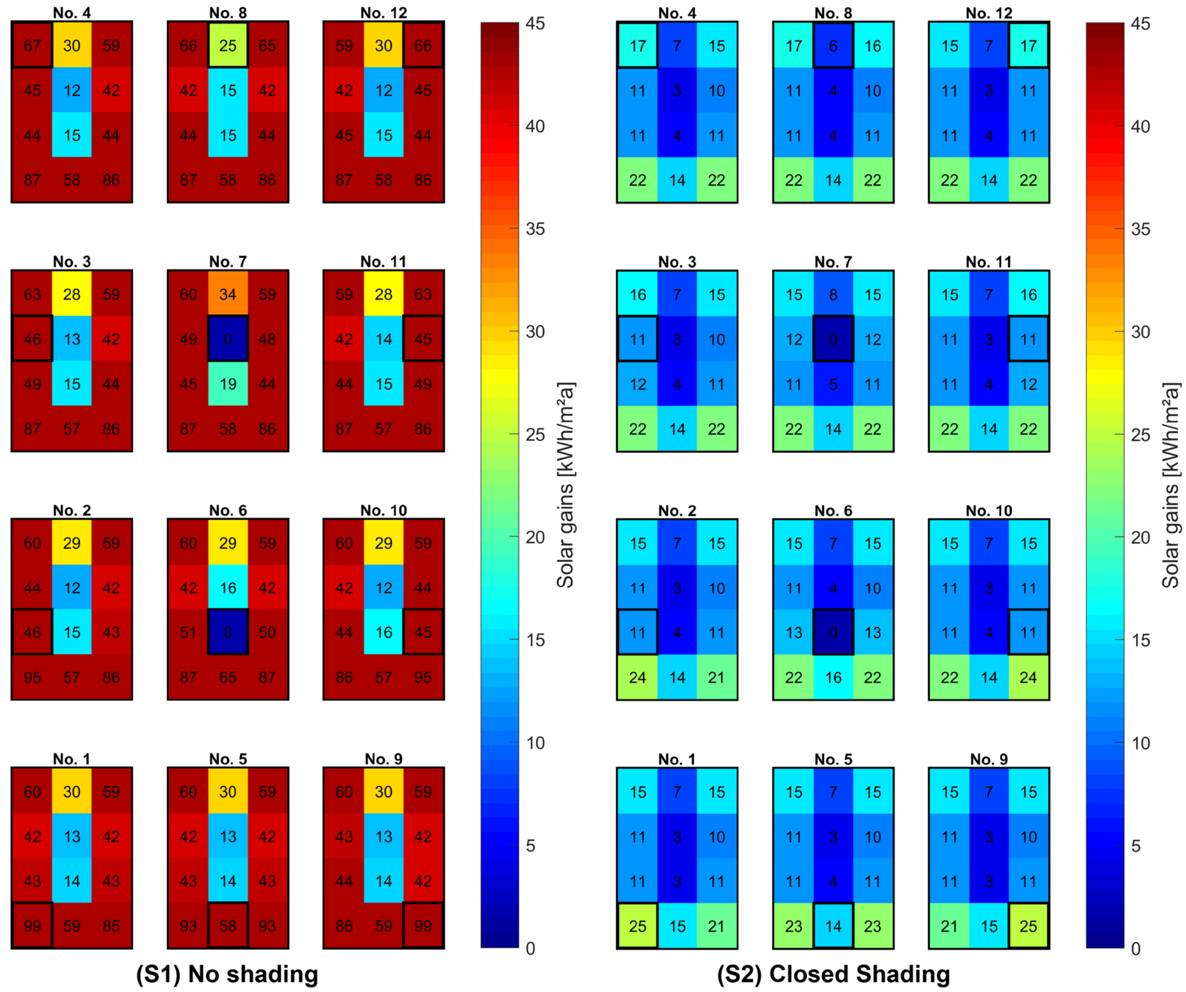


Figure 62. Comparison of solar gains for variants with no shading (S1) and closed shading (S2), IHC with room-based zoning

First, the variants with no shading (S1) and closed shading (S2) are compared. In Figure 62, the solar gains for the space layout designs no. 1–12 for both variants are shown. Overall, the results show that high solar gains are obtained for the variants with no shading (S1) compared to the variants with a closed shading (S2). For both variants, the solar gains in the airnodes located at the south façade are higher than for the other airnodes in the office space.

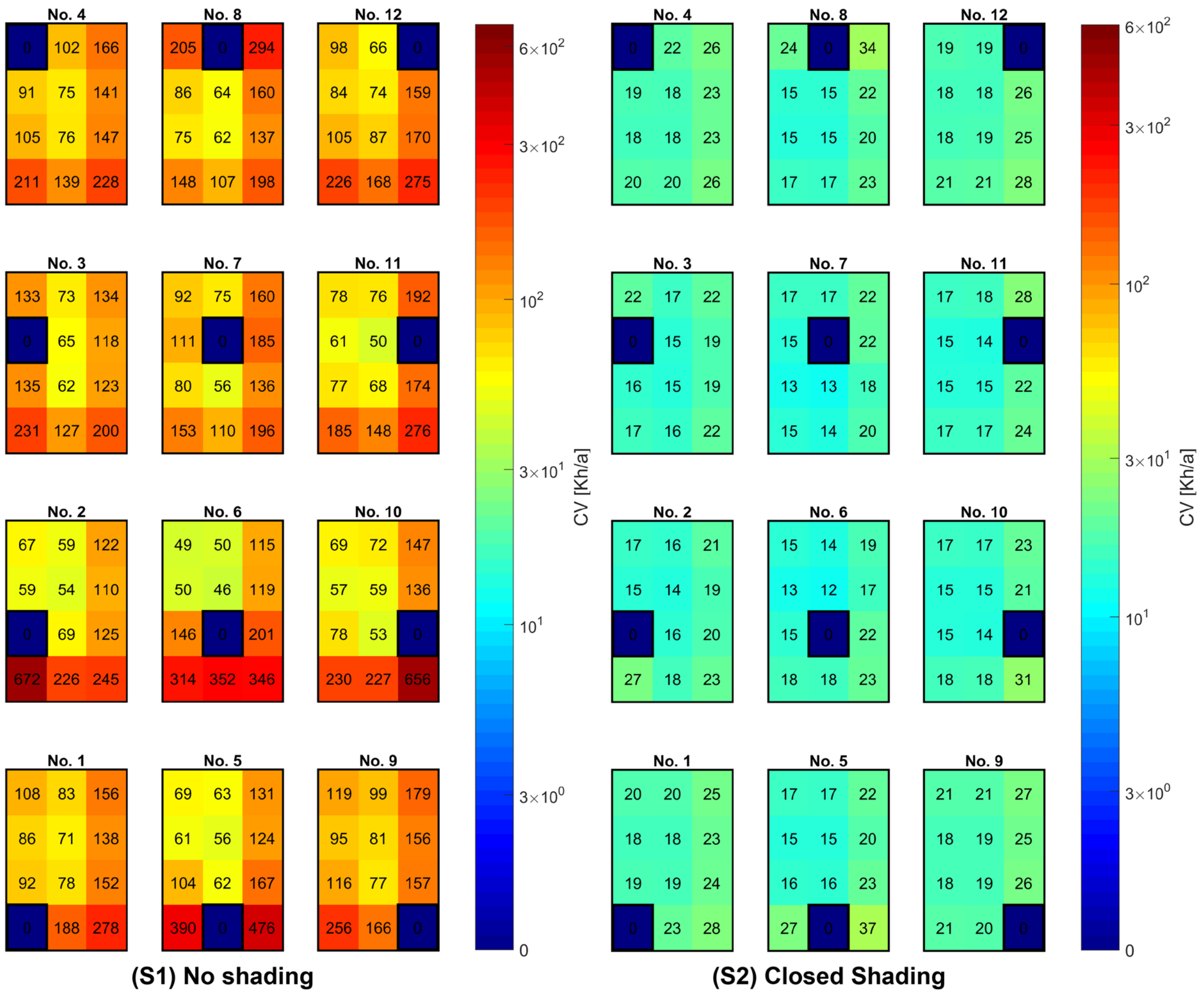


Figure 63. Comparison of CV for variants with no shading (S1) and closed shading (S2), IHC with room-based zoning

In addition, Figure 63 illustrates the result for the comfort violations (CV) for the space layout designs no. 1–12 for the variants with no shading (S1) and closed shading (S2). Here, it is clearly shown that for variants with no shading device (S1), the CV for almost all airnodes in the open-plan office are above the comfort limit of 63 Kh/a. Moreover, it shows that the solar radiation has a significant impact on the spatial distribution of the CV in open-plan office. In contrast, for the variants with a closed shading (S2), less CV are obtained and they are more evenly distributed in the open-plan office. As a result, it can be said that if more solar radiation is entering the office space, such as in variants with no shading (S1), higher variations in the spatial distribution of the CV, and thus also operative temperature occur in the open-plan office. Furthermore, an office space without shading device is not recommended, because of the high CV, especially at the south and east façade. However, even though a permanently closed shading device results in low CV, this design variants is not practical, because no direct daylight can enter the space. Therefore, different control strategies for the shading are tested and evaluated in the following.

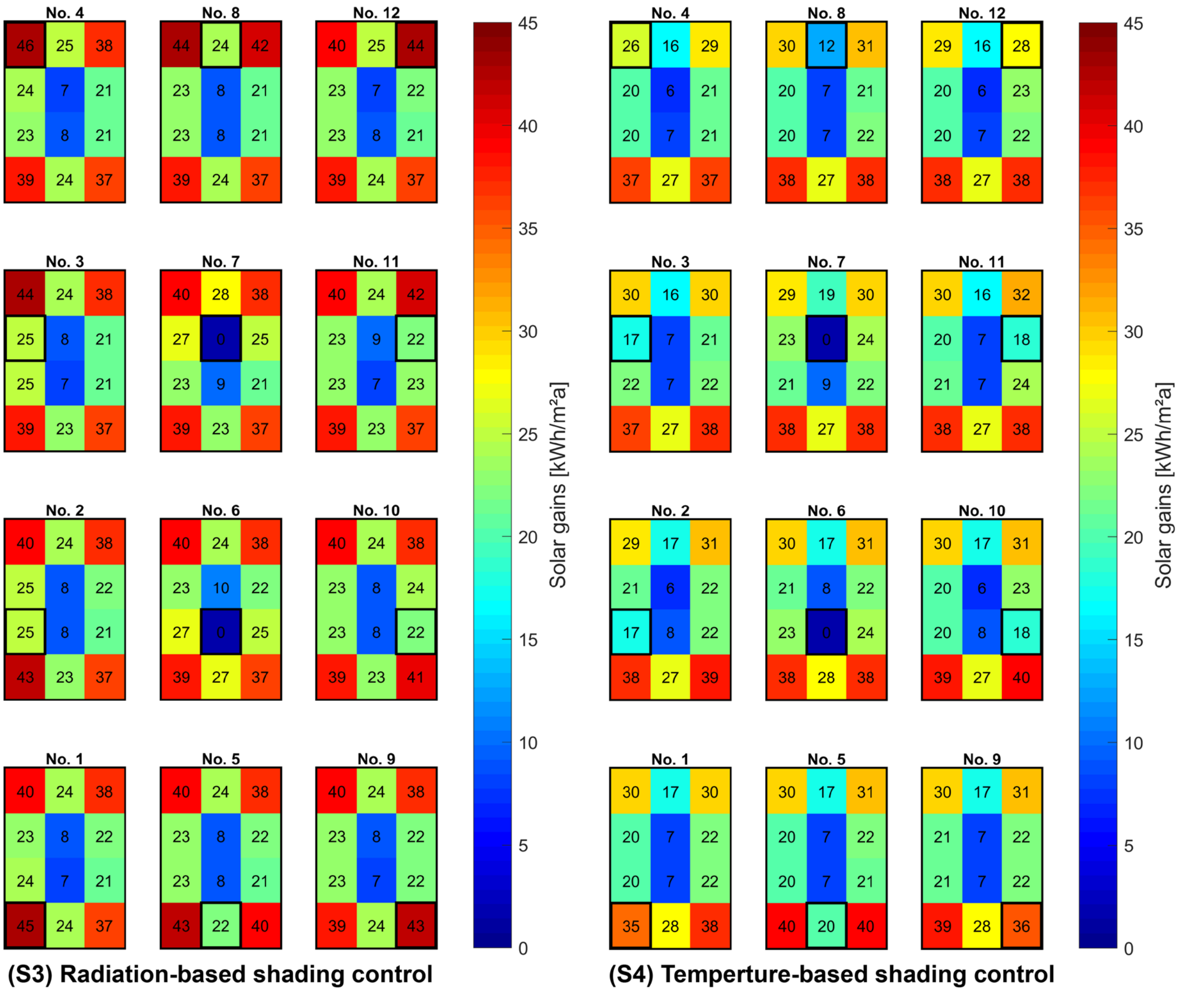


Figure 64. Comparison of solar gains for variants with radiation-based shading control (S3) and temperature-based shading control (S4), IHC with room-based zoning

Secondly, the variants with radiation-based shading control (S3) and temperature-based shading control (S4) are compared. In Figure 64, the solar gains for the space layout designs no. 1–12 for both variants are shown. For the variants with a radiation-based shading control (S3), high solar gains are obtained for all corner areas. In contrast, for the variants with a temperature-based shading control (S4), the corner areas in the north obtain less solar gains than the corner areas in the south. This can be explained by the additional temperature-based control of the shading: If the air temperature in an airnode are above the cooling set point, defined in Equation (4-1)–(4-3), the shading is closed, independent from the solar radiation. In airnodes located at the north façade, the temperature-based shading control can be beneficial, because the direct solar radiation that is entering the airnodes through the window is low, but still high temperature can be reached, because of the diffuse solar radiation. Therefore, a temperature-based shading control (S4) is recommended for airnodes located at the north façade.

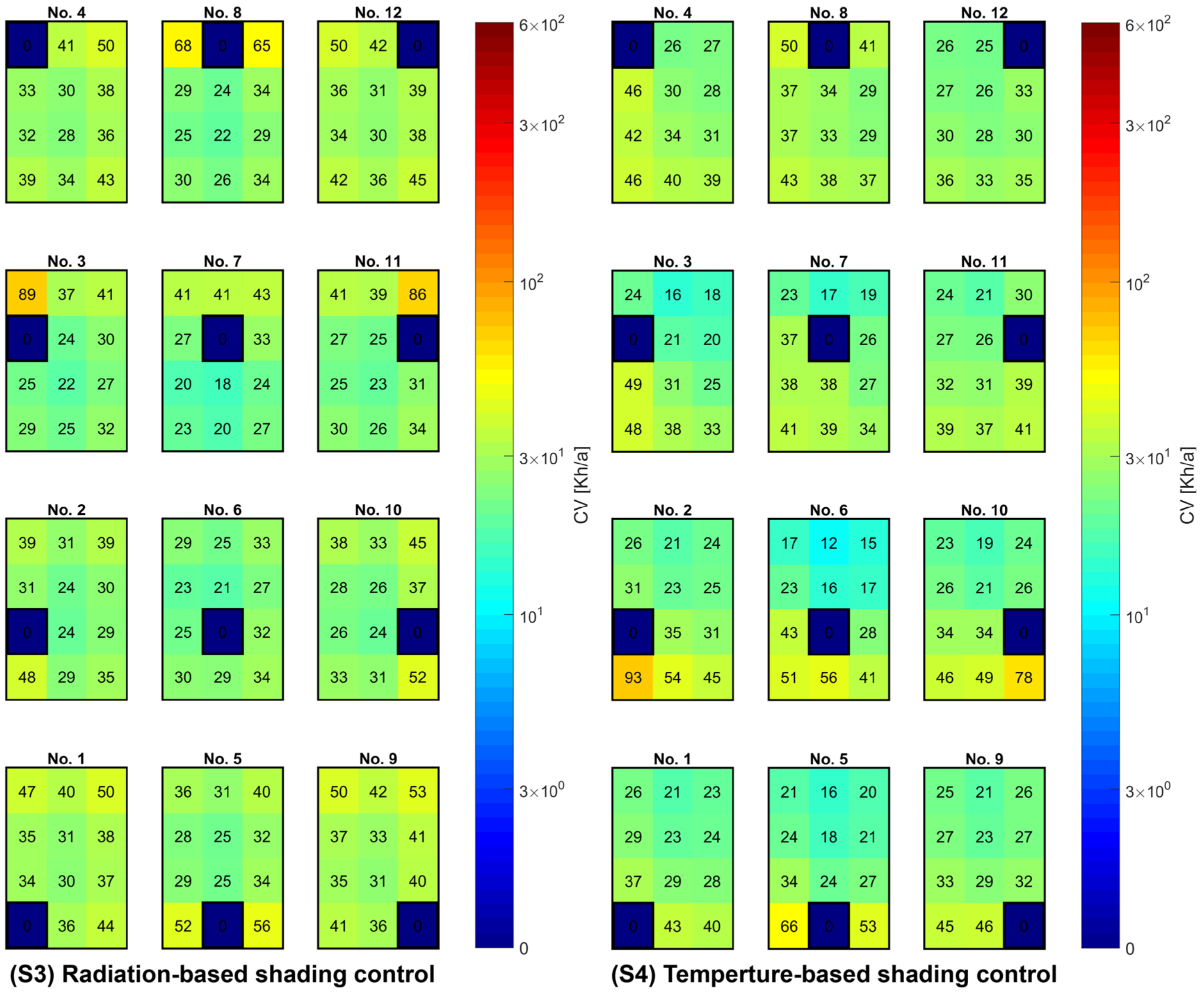


Figure 65. Comparison of CV for variants with radiation-based shading control (S3) and temperature-based shading control (S4), IHC with room-based zoning

In addition, Figure 65 illustrates the result for the comfort violations (CV) for the space layout design variants no. 1–12 for the variants with radiation-based shading control (S3) and temperature-based shading control (S4). Here, it is clearly shown that the shading control has only a small influence the overall thermal comfort in the open-plan office. However, the spatial distribution of the CV varies depending on the shading control strategy. For most variants with radiation-based shading control (S3), higher CV are obtained in the north airnodes and for most variants with radiation-based shading control (S3), higher CV are obtained in the south airnodes. Therefore, in this case it is not possible to make a clear statement about which shading control should be preferred.

Appendix B

Study on Internal Gains

In office buildings, internal gains from people, equipment and lighting contribute significantly to the building's heating and cooling energy demand. Thus, a reasonable assumption for the internal gains and their schedules is important when investigating office spaces. In the following, a comparison between different applicable standards to define internal gains and their schedules is presented. Here, three standards, which are completely define the internal gains and their schedules for an open-plan office and a meeting room, are compared: the German standard DIN V 18599 [88], the European standard DIN EN 16798 [105] and the Swiss Standard SIA 2024 [106]. The German standard defines a range of values for the parameters: In this study, the variant with the lowest values is referred to as "DIN 18599 low", the variant with the medium values is referred to as "DIN 18599 medium" and the variant with the highest values is referred to as "DIN 18599 high". Moreover, for comparison the internal gains and schedules, which are assumed in the case study presented in sections 4.2–4.2.5 are illustrated, too.

B.1 Internal Gains in the Open-plan Office

In Figure 66, the schedules of the total internal gains in an open-plan office for the different standards are illustrated. Further details can be obtained from Figure 67, which shows the schedules of internal gains from people, Figure 68, which shows the schedules of internal gains from equipment and Figure 69, which shows the schedules of internal gains from lighting.

For an open-plan office, the DIN EN 16798 shows the overall lowest internal gains compared to the other standards. The internal gains and schedules for people and equipment are simular for the DIN EN 16798 and SIA 2024. However, the internal gains from lightling defined in SIA 2024 are the highest. In total, the DIN V 18599 covers a wide range of values, especially for the internal grains from equipment.

In the case study, it is assumed for the open-plan office that each person is equiped with one laptop and two screens. Moreover, one printer for the complete floor is assumed and the lighting is turned off during midday. Thus, the resulting internal gains and schedules are slightly higher than the values assumed in SIA 2024, but lower than the highest values assumed in DIN V 18599.

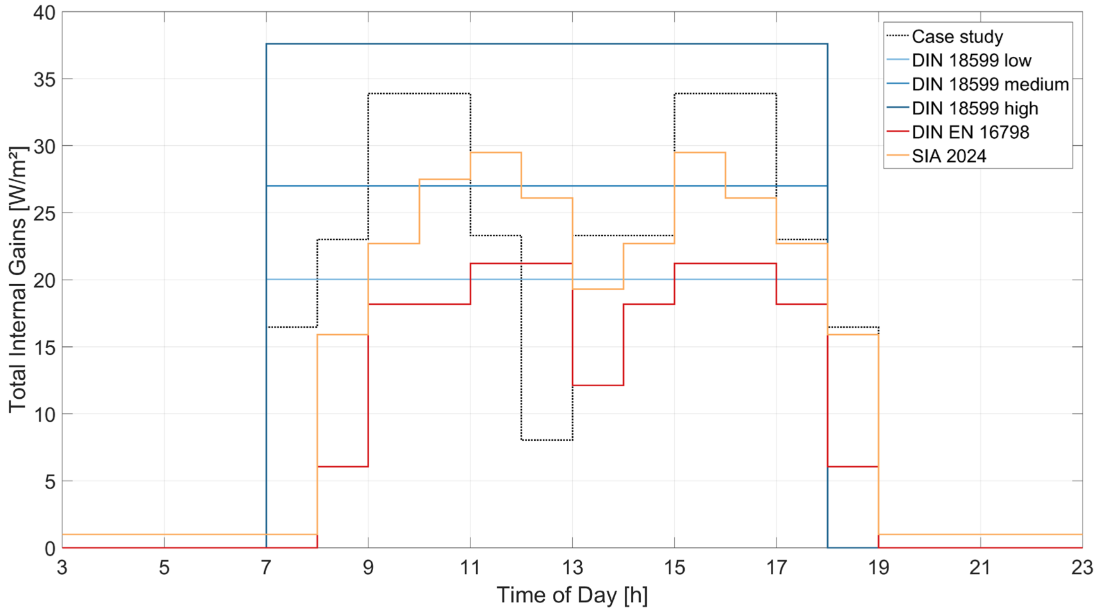


Figure 66. Comparison of total internal gains in open-plan office

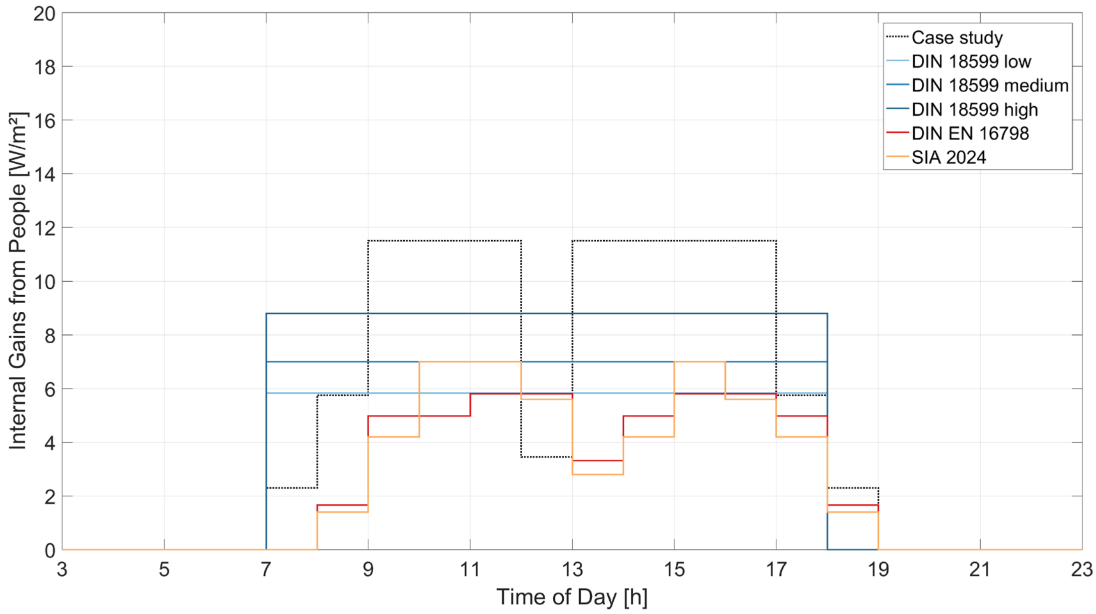


Figure 67. Comparison of internal gains from people in open-plan office

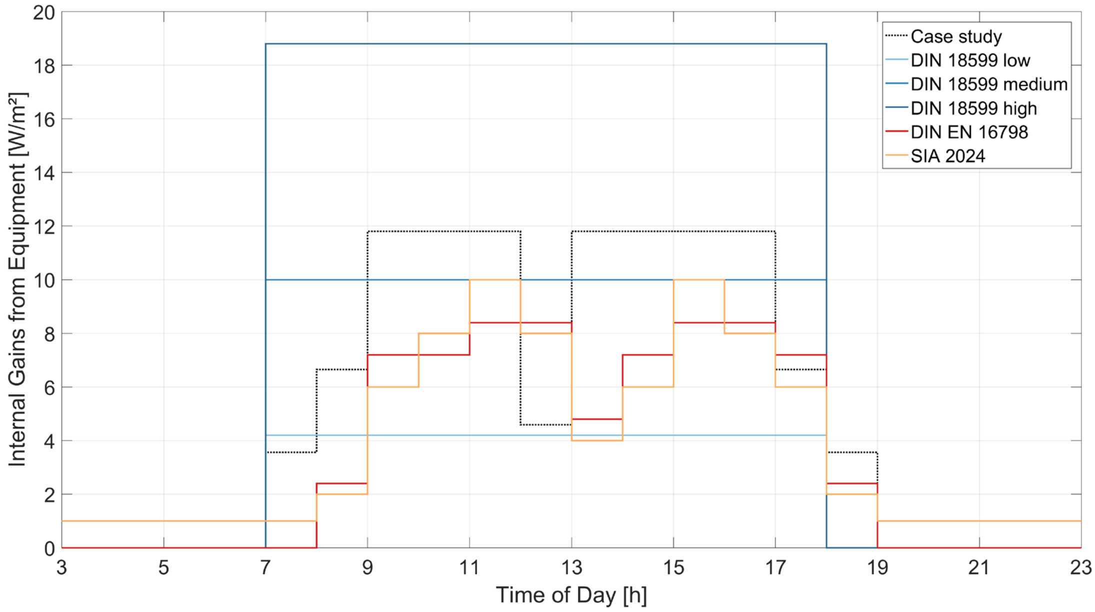


Figure 68. Comparison of internal gains from equipment in open-plan office

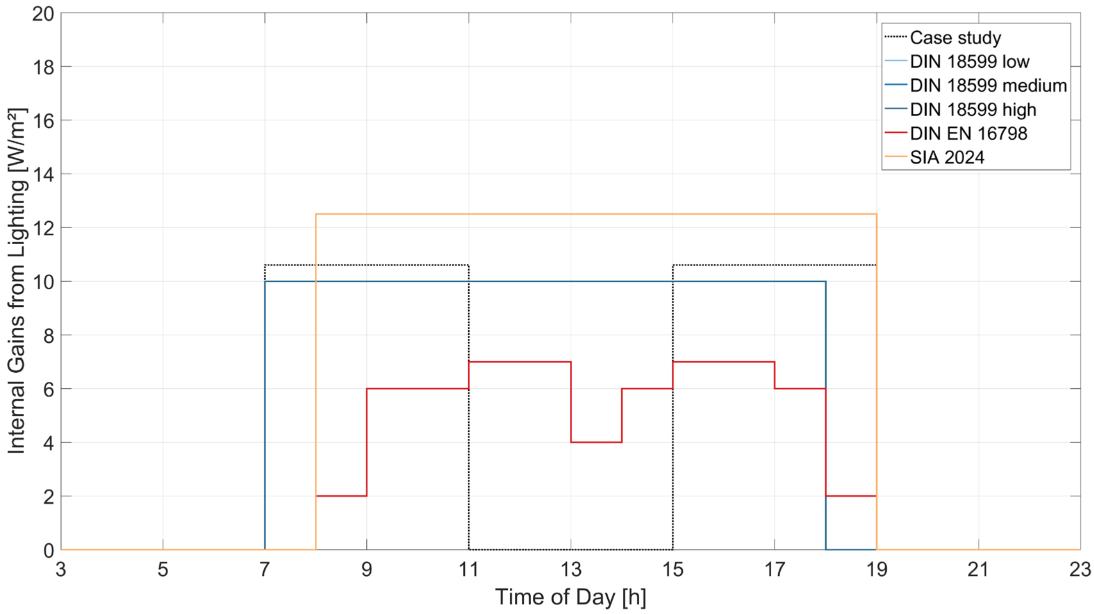


Figure 69. Comparison of internal gains from lighting in open-plan office

B.2 Internal Gains in the Meeting Room

In Figure 70, the schedules of the total internal gains in a meeting room for the different standards are illustrated. Further details can be obtained from Figure 71, which shows the schedules of internal gains from people, Figure 72, which shows the schedules of internal gains from equipment and Figure 73, which shows the schedules of internal gains from lighting.

It should be noted that the values in DIN EN 16798 for the internal gains from people are corrected according to the same heat gains per person as for the open-plan office (141.1 W per person). Moreover, an area per person of 2 m^2 is assumed, as presented for an meeting room in the Annex B7 p. 64 [105].

For a meeting room, the DIN EN 16798 shows the overall highest internal gains compared to the other standards. This is mainly due to the high internal gains from people and equipment. In contrast, the SIA 2024 and DIN V 18599 show comparatively low internal gains from equipment. One possible explanition could be that these standards do not consider laptops or other advices, which are brought to the meeting room. However, in most offices, this is common practice.

Therefore, in the case study, it is assumed that each person brings one laptop to the meeting. Moreover, one projector is assumed in the meeting room and the lighting is turned off during absence. Thus, the resulting internal gains and schedules are higher than the values assumed in SIA 2024 and DIN V 18599, but lower than the values in DIN EN 16798.

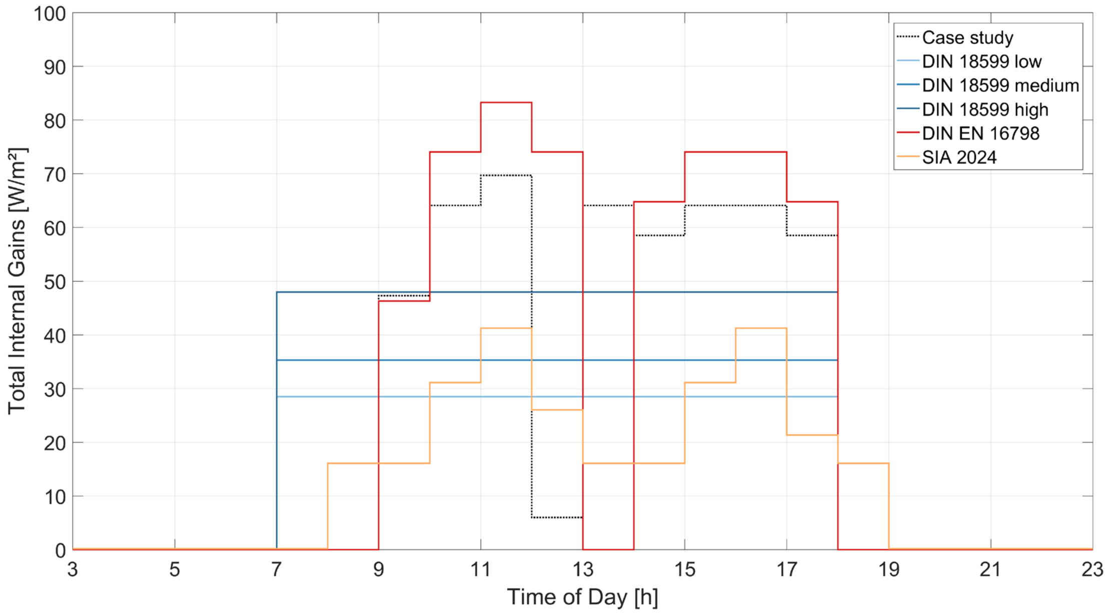


Figure 70. Comparison of total internal gains in meeting room

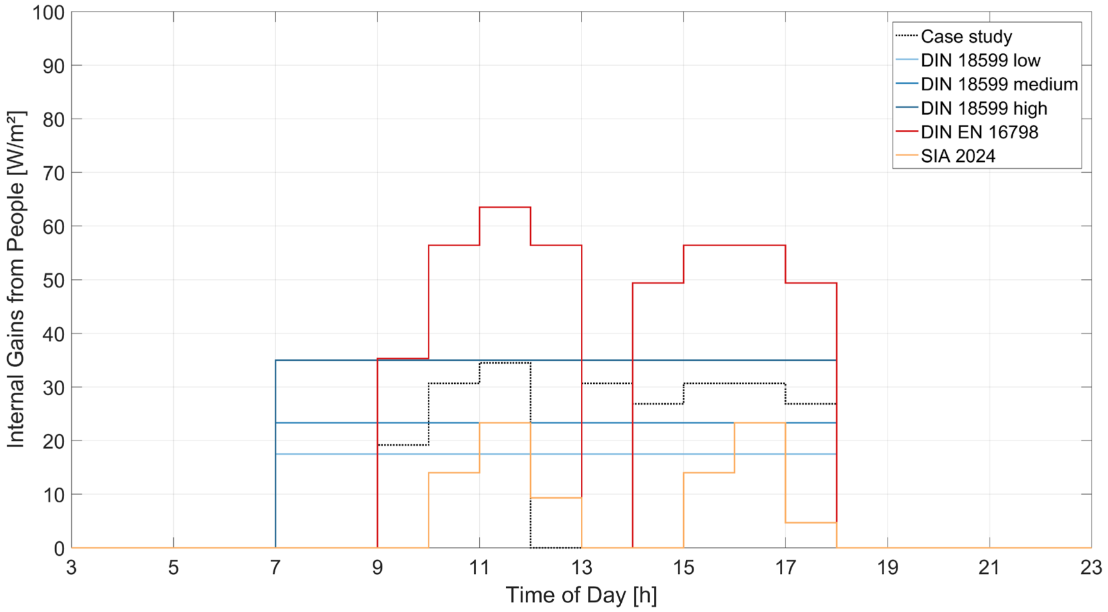


Figure 71. Comparison of internal gains from people in meeting room

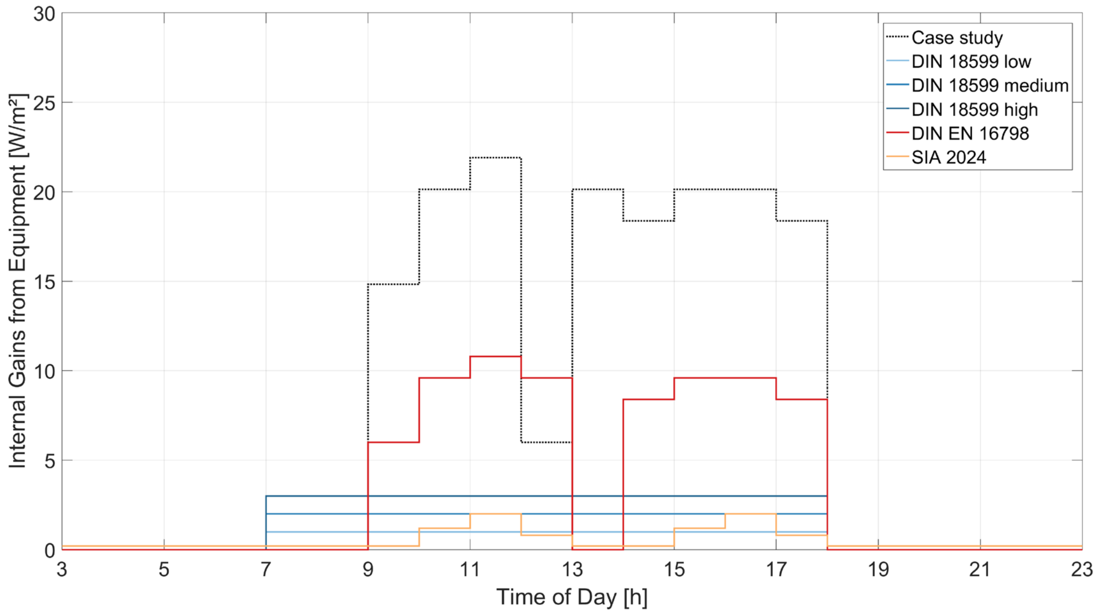


Figure 72. Comparison of internal gains from equipment in meeting room

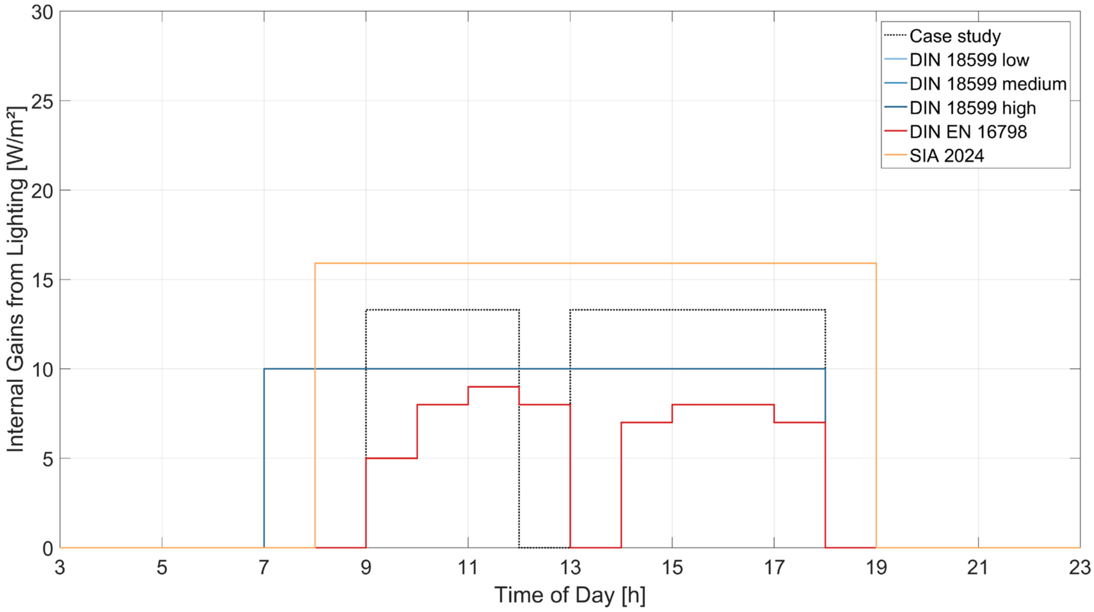


Figure 73. Comparison of internal gains from lighting in meeting room

Appendix C

Construction Parameters

C.1 Radiant Ceiling Construction

In the Table 18, all construction parameters for the radiant ceiling (RC), which are assumed in the simulation setup in TRNSYS 18 [38], are listed.

Table 18. RC detailed construction parameters (based on [92])

Parameters	Construction
Pipe spacing	0.08 m
Pipe diameter	0.01 m
Pipe length	120 m
Module area	9.94 m^2
Active area	5.76 m^2
Constant (k)	9.0115
Exponent (n)	1.083
Specific norm flow	37 $\frac{kg}{h \cdot m^2}$
Cooling power	86 $\frac{W}{m^2}$
Heating power	60 $\frac{W}{m^2}$
Percentage of total ceiling area	58 %
Fluid supply temperature for heating	35 °C
Fluid supply temperature for cooling	18 °C

C.2 TABS Construction

In Table 19, all construction parameters for the radiant ceiling (RC), which are assumed in the simulation setup in TRNSYS 18 [38], are listed.

Table 19. TABS detailed construction parameters (based on [94])

Parameters	Construction
Pipe spacing	0.2 m
Pipe diameter	0.02 m
Pipe length	80 m
Pipe thickness	0.0025 m
Conductivity	$0.35\ \frac{\mathrm{W}}{\mathrm{m \cdot K}}$
Specific mass flow	$19\ \frac{\mathrm{kg}}{\mathrm{h \cdot m^2}}$
Cooling power	$50\ \frac{\mathrm{W}}{\mathrm{m^2}}$
Heating power	$40\ \frac{\mathrm{W}}{\mathrm{m^2}}$
Percentage of total ceiling area	80 %

Appendix D

Extended Results

In the following, additional figures of the results presented in section 5.3 are illustrated.

D.1 HVAC System Configuration No. 1: Only Mechanical Ventilation

Figure 74 shows the CV for the space layout design variants no. 1–12 with a core/perimeter zoning and a north/south zoning of the MV system.

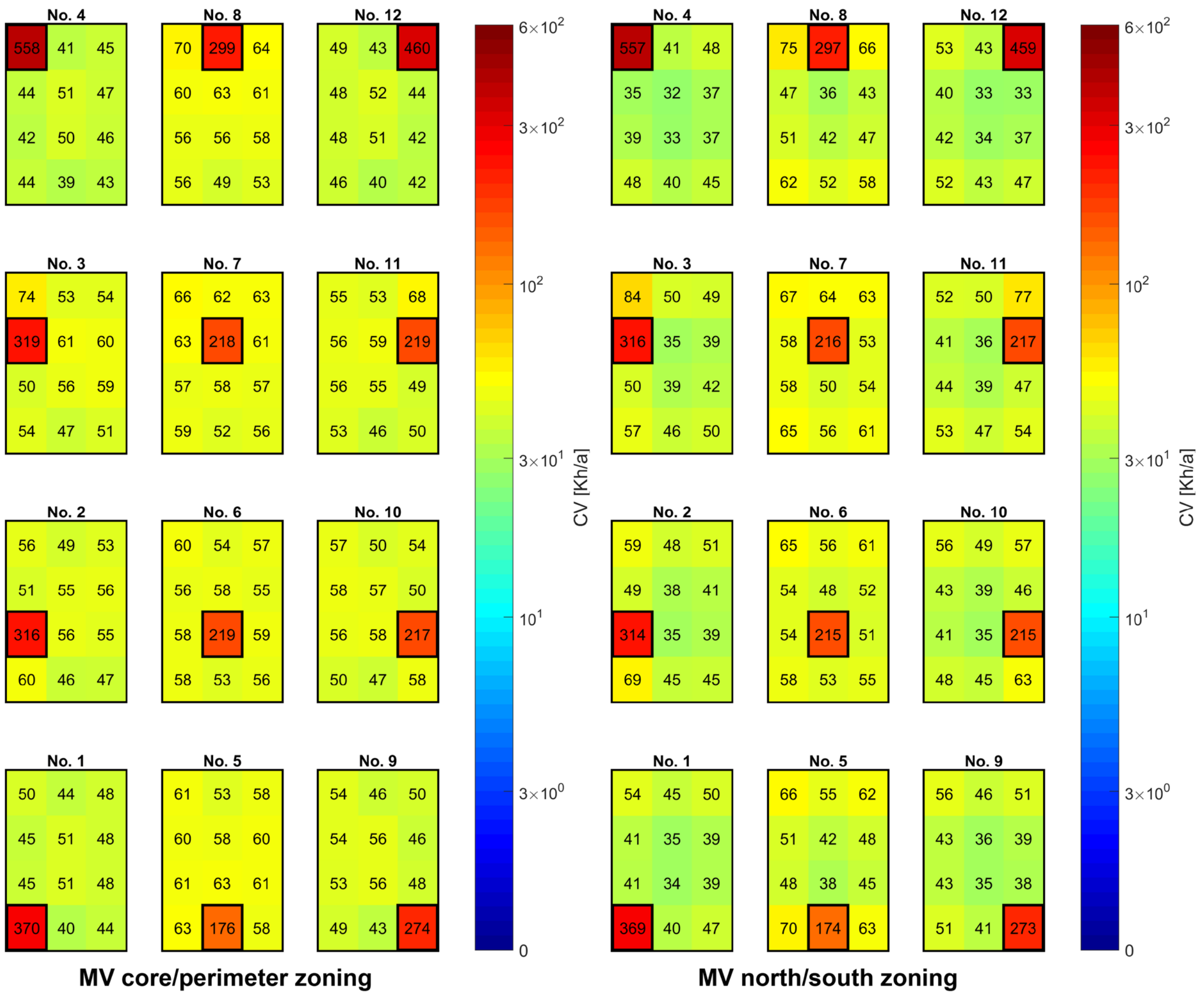


Figure 74. MV – comparison of CV for space layout variants no. 1–12 for core/perimeter and north/south zoning

In Figure 75, the EUI for the space layout design variants no. 1–12 with a fine-grained and a room-based zoning of the MV system is illustrated.

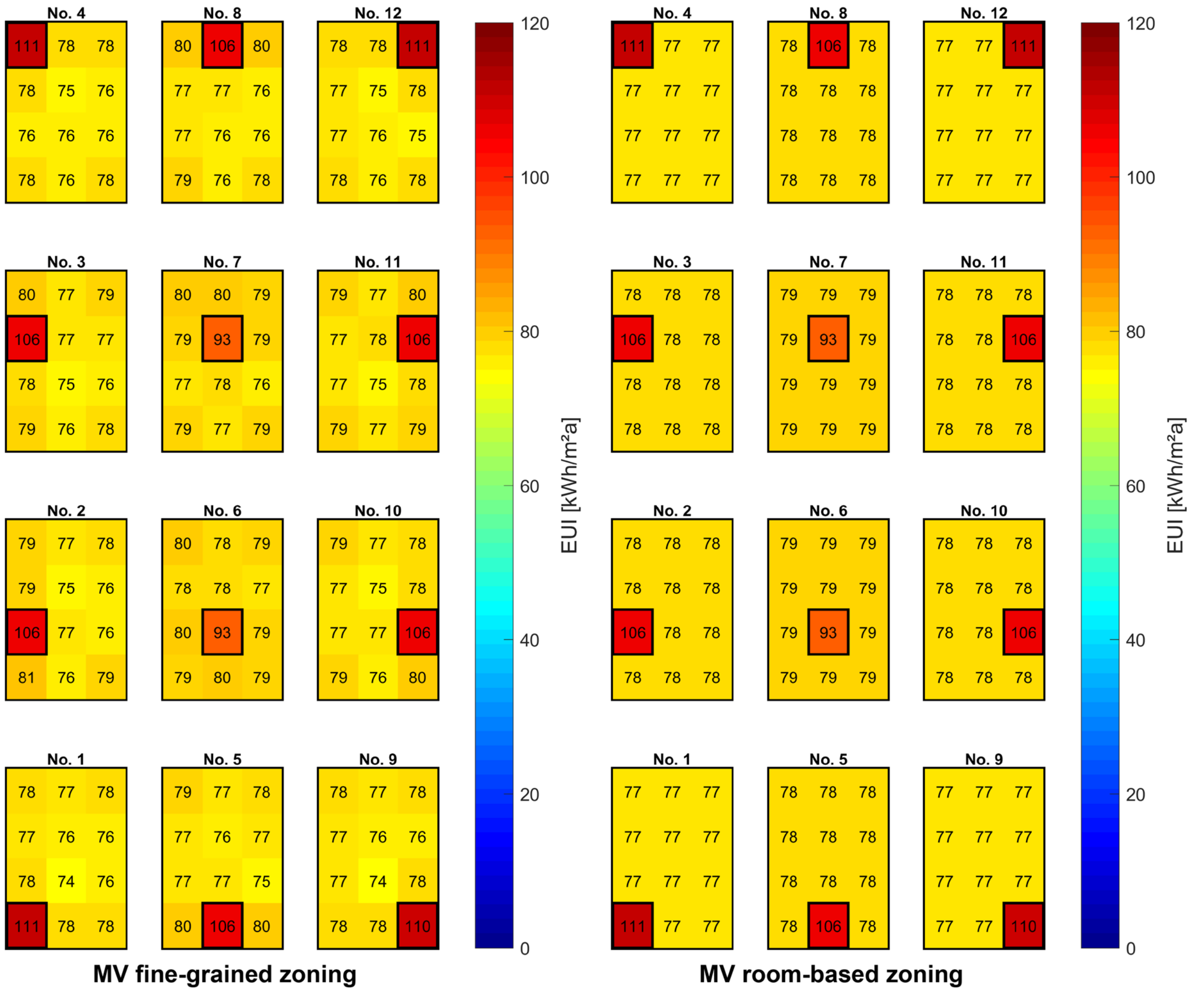


Figure 75. MV – comparison of EUI for space layout variants no. 1–12 for fine-grained and room-based zoning

In Figure 76, the EUI for the space layout design variants no. 1–12 with a core/perimeter and a north/south zoning of the MV system is illustrated.

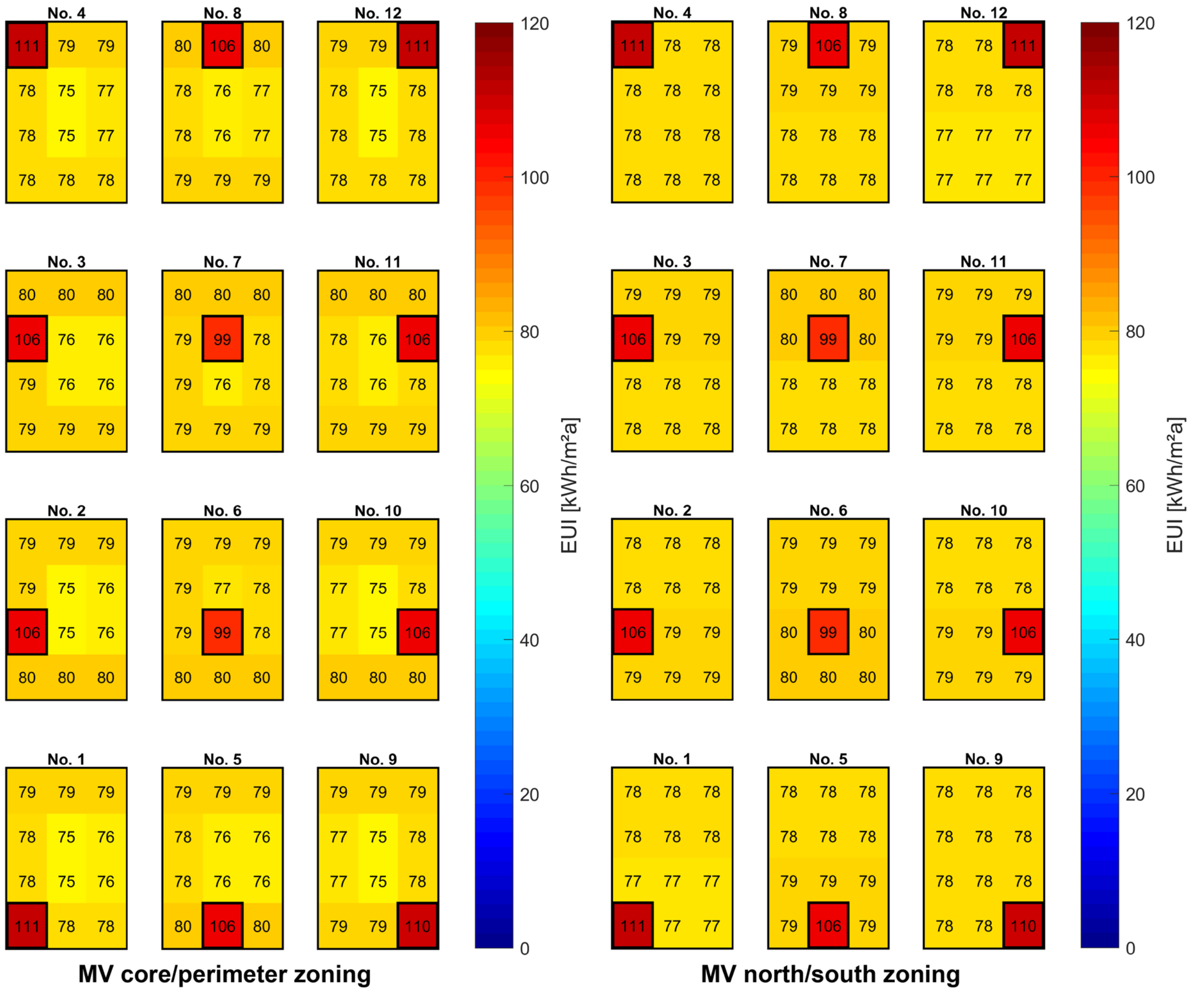


Figure 76. MV – comparison of EUI for space layout variants no. 1–12 for core/perimeter and north/south zoning

D.2 HVAC System Configuration No. 2: Radiant Ceiling

Figure 77 shows the CV for the space layout design variants no. 1–12 with a core/perimeter and a north/south zoning of the RC system.

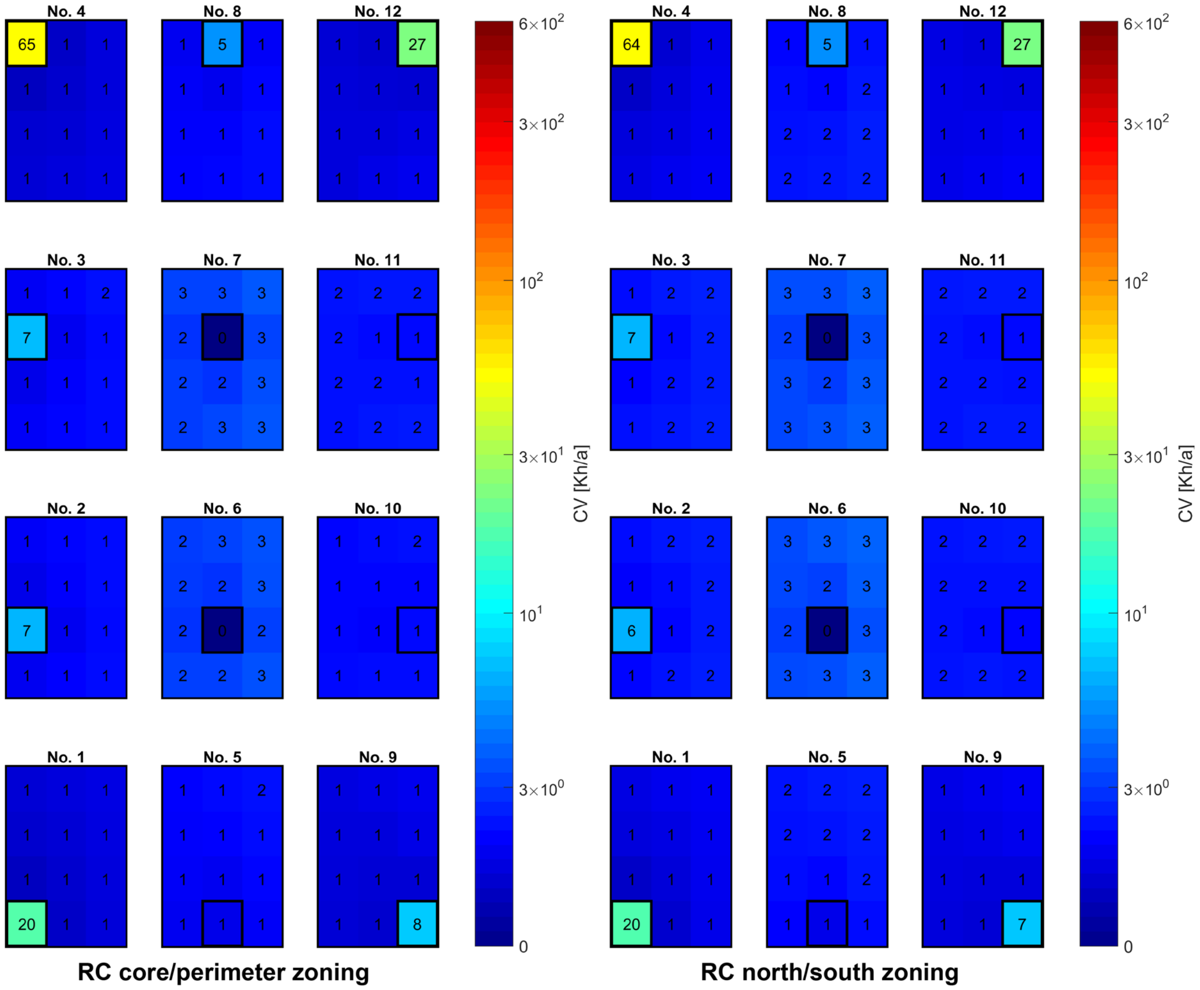


Figure 77. RC – comparison of CV for space layout variants no. 1–12 for core/perimeter and north/south zoning

In Figure 78, the heating and cooling energy demand for the space layout design variants no. 1–12 with a core/perimeter zoning of the RC system are illustrated.

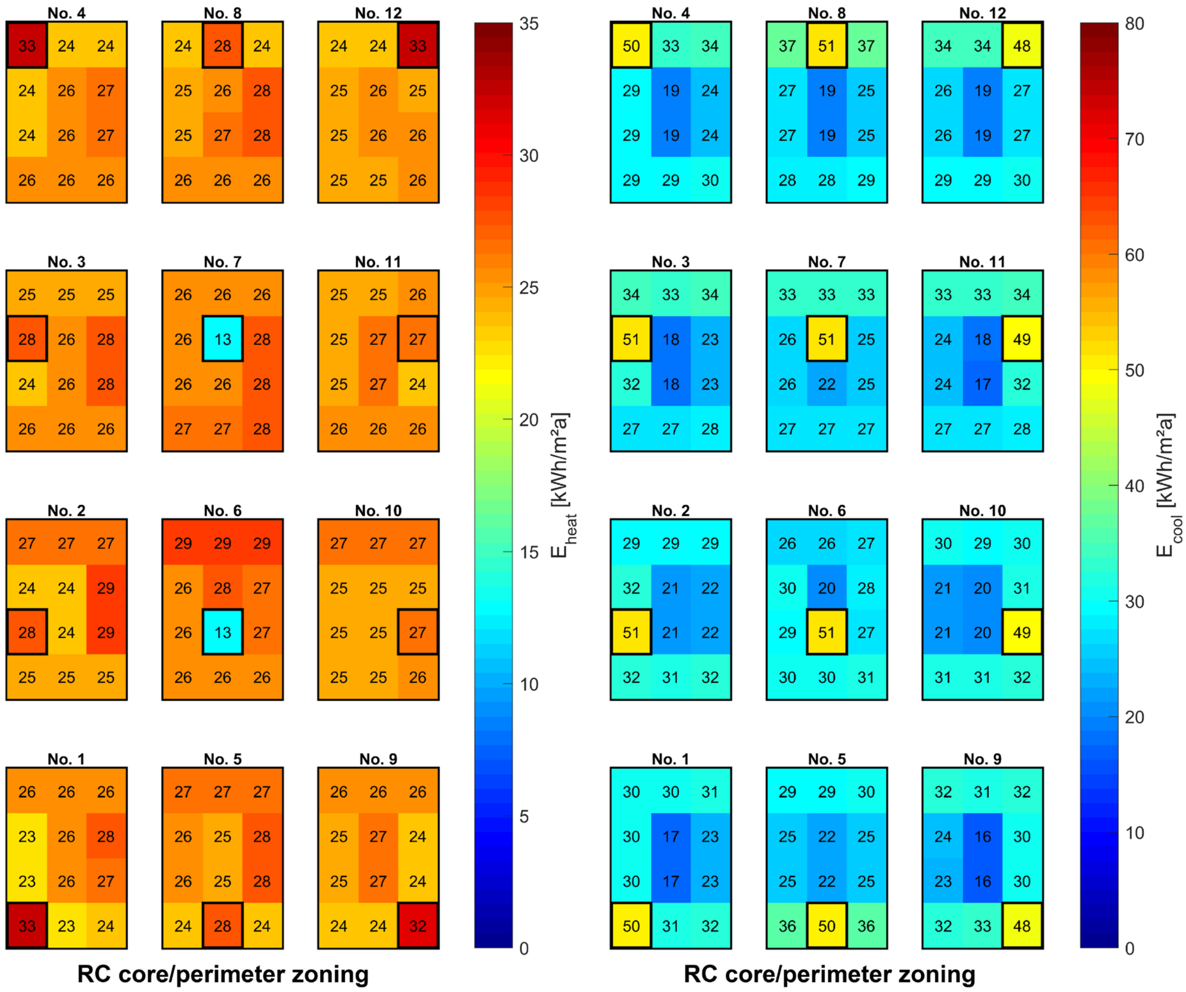


Figure 78. RC – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 for core/perimeter zoning

In Figure 79, the heating and cooling energy demand for the space layout design variants no. 1–12 with a north/south zoning of the RC system are illustrated.

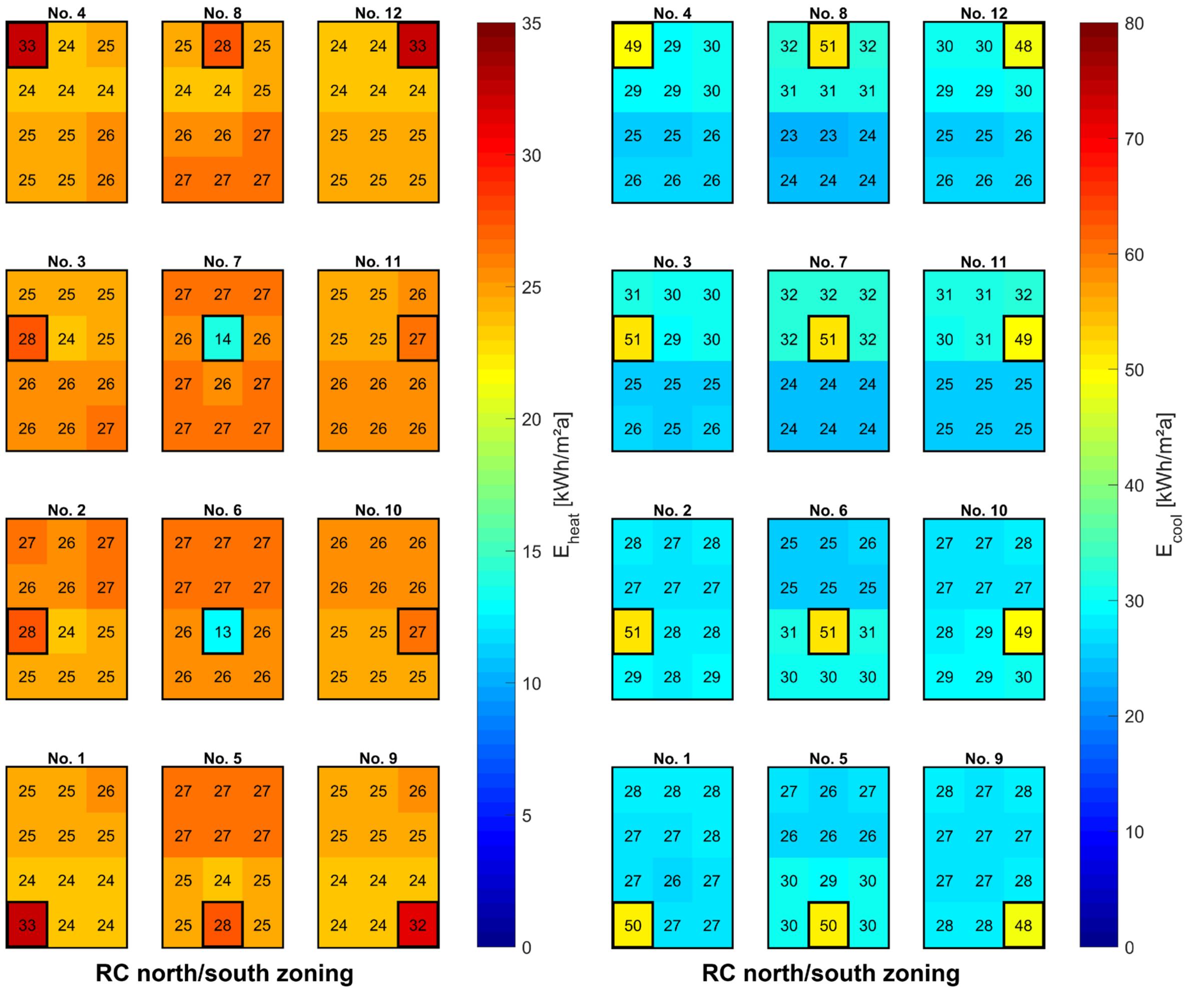


Figure 79. RC – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 for north/south zoning

In Figure 80, the heating and cooling energy demand for the space layout design variants no. 1–12 with a room-based zoning of the RC system are illustrated.

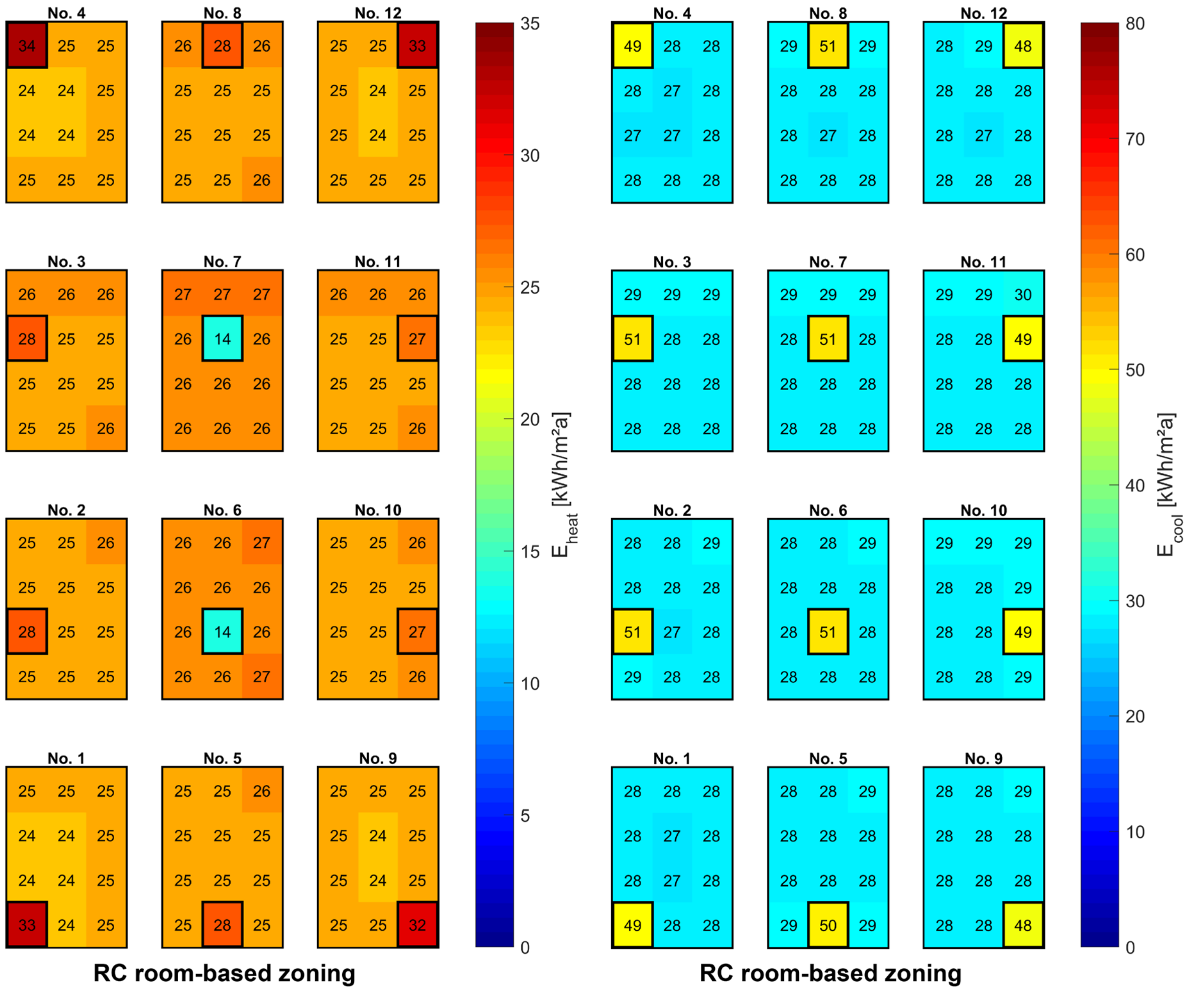


Figure 80. RC – comparison of E_{heat} and E_{cool} for space layout variants no. 1–12 for room-based zoning

In Figure 81, the EUI for the space layout design variants no. 1–12 with a fine-grained and a room-based zoning of the RC system is illustrated.

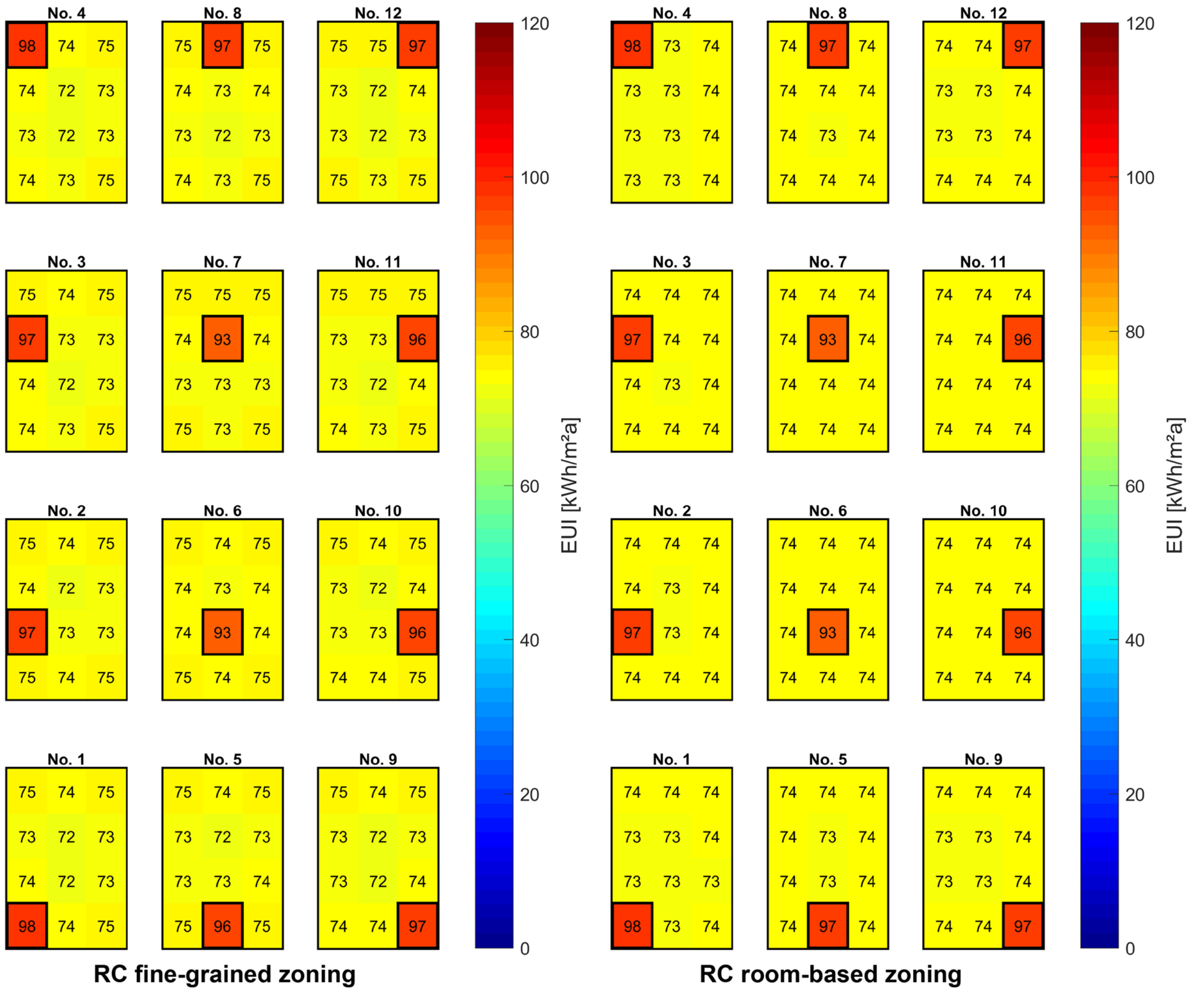


Figure 81. MV – comparison of EUI for space layout variants no. 1–12 for fine-grained and room-based zoning

D.3 HVAC System Configuration No. 3: TABS

In Figure 82, the EUI for the space layout design variants no. 1–12 for TABS with three and one HC is illustrated.

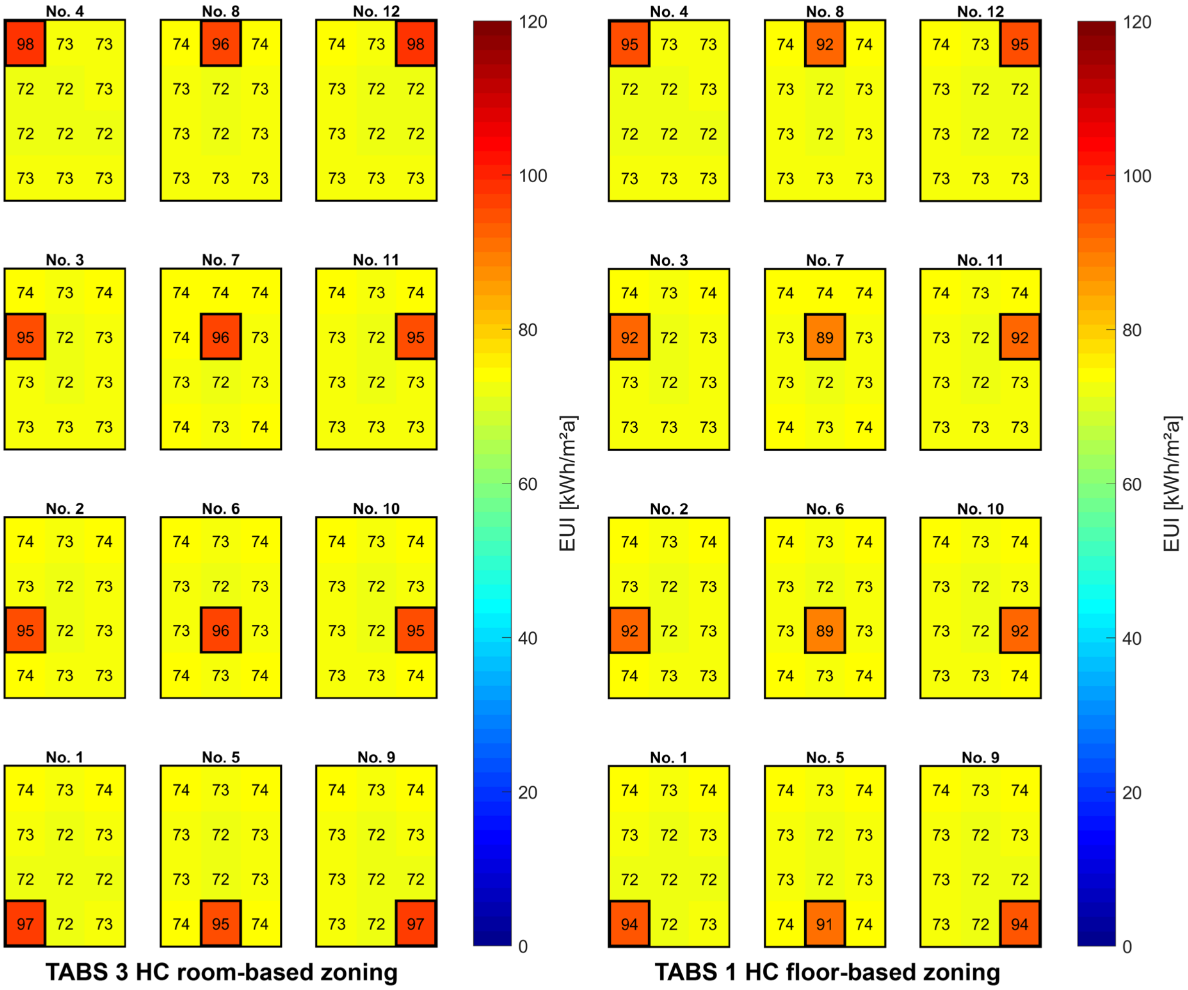


Figure 82. TABS – comparison of EUI for space layout variants no. 1–12 with 3 HC and 1 HC