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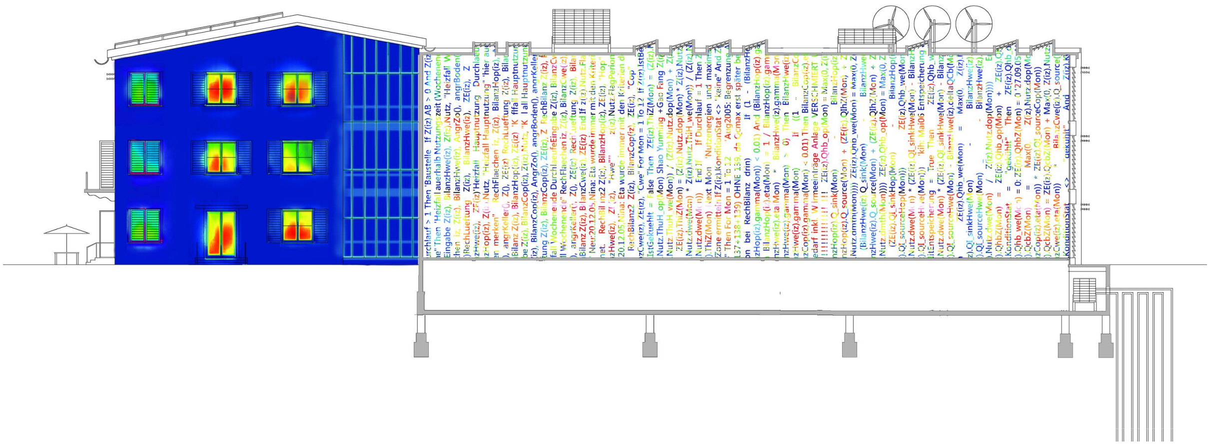

Dissertation

A systematic approach to energy efficiency retrofit solutions for existing office buildings

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Ingenieurfakultät Bau Geo Umwelt

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Abstract

The existing office building stock is an important object for energy retrofits to substantially reduce the global energy consumption and improve the environment. In an energy retrofit project, the selection and integration of energy efficiency measures that can satisfy stakeholders' diverse, and often conflicting requirements is of great importance. The current study establishes a new methodology to support design teams in making informed multi-criteria decisions for energy-efficiency retrofit solutions at the early design stage. The fundamental feature of the framework is the integration of an analysis procedure carried out by a design team and a numerical optimization procedure using a computer. Such an interaction is necessary as building design and retrofits have various qualitative components that demand human judgment. In contrast to previous approaches, this study provides an integrated framework to identify the stakeholders' requirements and potential energy efficiency measures, to build and optimize a large design space, and to determine the best solutions, in a holistic way. In addition, mathematical optimization and evaluation techniques are incorporated into the decision making process, which simultaneously considers the important role of stakeholders in carrying out the analysis procedure.

An office building in Germany needing an energy retrofit serves as an illustrative example of the methodology development. In addition, the implementation of the new methodology is thoroughly examined in a detailed case study of a representative office building in northern China. A set of retrofit principles that are generally applicable to the same type of building in northern China, where both heating and cooling are required, is established. A model based on multi-criteria decision making method is then proposed which helps the stakeholders to better understand and select the potential optimal solutions in a holistic approach. Another aspect of building retrofit design is that real-world construction activities do not take place in a deterministic manner, and most systems behave stochastically – involving variation or probability. Thus, a Monte-Carlo based uncertainty analysis model, which addresses the design uncertainties and investigates the reliability and robustness of design solutions, is established. In general, the proposed methodology provides a platform to select and integrate energy efficiency measures for optimal office building retrofit solutions.

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Chapter 1

Introduction

1.1 Background and problem statement

The existing office building stock is an important sector in energy consumption. The proportion of public buildings in the whole building sector is about 25% in Europe with 1,200 million square meters of floor space for office buildings [1]. Studies have found that the energy consumption level of office buildings falls in a wide range and is relatively high. According to Burton and Sala [2], the range is between 100 and 1000 kWh/m^2 for the yearly delivered total energy consumption of European office buildings. In China, public buildings account for 34% of the urban building sector. However, they constitute 56% of the total urban building stock energy consumption (excluding district heating) [3]. Under such situation, energy retrofits of office buildings must be put into a crucial position.

An energy retrofit project relies on the selection and integration of energy efficiency measures (EEMs) that can satisfy stakeholders' diverse, and often conflicting requirements. A successful project needs adequate consideration of possible EEMS and adequate consideration of stakeholder requirements. De Wilde reveals that in overall building design projects, "approximately 80% of all EEMs are selected without considering alternatives, which demonstrates that the decision to select a specific measure is highly intuitive" [4]. On the other hand, design solutions also relate to the achievement of stakeholder satisfaction and the optimization of the total value of a project design. A building's energy efficiency retrofit solution is a compromise between several stakeholders' requirements (e.g., investment costs, thermal comfort, energy saving). The stakeholders in this field include the owner, tenants, the design team consisting of designers, and consultants from multiple disciplines, etc. It is found that stakeholders usually have fragmented expertise, varying and, in most cases, conflicting requirements [5]. How to integrate different points of view for a satisfactory assessment of the retrofit design is rather important. Therefore, the development of a systematic approach which supports design teams in making informed multi-criteria decisions for energy-efficiency retrofit solutions in the early design phase is needed. In this dissertation, the research hypothesis states:

In the context of office building retrofits, the performance of buildings can be improved *tremendously by giving the designers the chance to make informed decisions on energy efficiency solutions by aligning the multiple and in most of the cases conflicting objectives, and a large number of potential EEMs in the early design phase.*

The hypothesis asserts that the establishment of a methodology and tool that support decision-makers in making informed decisions on energy efficiency solutions in the early design stage is of great significance.

1.2 Research objectives

In this doctoral research, the basic idea is to implement the methodologies of requirement analysis, multi-objective optimization, and multi-criteria decision analysis in the assessment of energy efficiency solutions in office building retrofit projects. In addition, a comprehensive prototype for stakeholders to commit themselves to sustainable development is proposed. Specifically, there are four goals of the research. The first goal is to develop a new methodology and prototype for the selection and integration of office building EEMs with respect to multiple criteria and constraints in the early design stage. The second goal is to implement the decision support methodology for the early design stage of retrofitting, which aligns the requirements of stakeholders and handles a large range of EEMs to obtain optimal energy efficiency retrofit solutions. An office building in Germany needing an energy efficiency retrofit will serve as an example to demonstrate the workflow along with the methodology development. In addition, the developed methodology fully applied in a detailed case study of a representative office building in northern China. The third goal is to estiblish a multi-criteria decision making model which allows stakeholders to better understand and handle the potential optimal solutions in a holistic way. The fourth goal is to develop an uncertainty analysis model to determine the reliability and robustness of the proposed strategies.

Of particular note is that the new approach must be applicable in the context of an ongoing office building retrofit design process. More specifically, the new approach must:

—be applicable during the early design stage of office building retrofits, since it is in these phases that designers evaluate the feasibility of retrofits and most EEMs are chosen;

—be limited to the selection and integration of EEMs. Selecting these EEMs is only one of many activities during the retrofit design process.

The work is of interest as it addresses actual cases of office building retrofits. The proposed methodology provides guidance to facility managers, engineers and specialized design consultants in collaboration with professional design teams.

1.3 Organization of the dissertation

The dissertation has eight chapters. Chapter 1: *Introduction* provides the research objectives, and the organization of the dissertation. Chapter 2: *Problem statement* presents the research motivation and the detailed problem definition. It summarizes the state-of-the-art of scientific studies in the areas of conflicting stakeholders' requirements, processes of energy efficiency retrofits, decision making methodologies, energy efficiency measures, and representative retrofit studies on office buildings. From the literature review, the detailed problem definition for the research is formalized.

Subsequently, Chapter 3: *Development of the methodology with an illustrative case study* introduces concepts and methodologies applied to an analysis procedure carried out by a design team and a numerical procedure of optimization carried out by computer. The structure the usability of the model are illustrated. In addition, an office building in Germany needing an energy efficiency retrofit serves as an example to explain the workflow of the proposed model.

A case study in northern China is carried out in Chapter 4: *Retrofitting office buildings in northern China*. It begins with an investigation of the current situation of the office building stock in China. The proposed methodology in chapter 3 is then deployed on a representative ordinary office building needing an energy retrofit. It is estimated that this type of ordinary office building makes up more than 95% of office buildings in China, and more than 70% of total office floor space. From the retrofit strategy of the case study, a few energy efficiency retrofit principles that are generally applicable to the same type of buildings in northern China are investigated, where both heating and cooling are required.

Chapter 5: *Multiple-criteria decision analysis on building retrofits* covers the analysis of multiple optimal solutions generated by the model in chapter 3. An evaluation model based on multi-criteria decision making method is developed which allows the stakeholders to better understand and handle the potential optimal solutions in a holistic way. An evaluation method is introduced with a structured approach for assessing the quality of designs. By applying this model, the single solution or a small set of alternative solutions that satisfies the stakeholders' preferences will be identified for further detailed design. The chapter continues with the solution analysis of the case study in northern China. The chapter ends with the conclusions of the analysis and a summary of the findings.

Chapter 6: *Uncertainty analysis* employs the Monte Carlo analysis method to deal with the stochastic behaviors of real-world construction activities — specifically the small deviations of design parameters and constraints in building retrofits. Thus the reliability and robustness of design solutions against the variations of the EEMs' design parameters can be quantitatively measured. The proposed solutions in the context of the two case studies are analyzed under three uncertainty conditions.

Chapter 7: *Discussion* combines and analyzes the work from the proceeding chapters. The discussions center around the goals defined in the problem statement above. The results show that the developed methodology provides a structured framework to achieve optimal retrofit solutions to enhance office buildings' energy efficiency performance and meet the needs of stakeholders. In addition, the limitations of the proposed methodology that are revealed in the case studies are also presented.

Chapter 8: *Conclusion and outlook* first summarizes the dissertation and lists the main research conclusions. In the outlook section, further research directions are discussed.

Chapter 2

Problem statement

2.1 Background

Building energy consumption accounts for almost 40% of the total primary energy use in the world [6]. It becomes obvious that there is a need of building energy efficiency through new constructions and energy retrofits for the sake of reducing global energy use. However, the new construction rate is only between 1.0-3.0% per annum in OECD (Organization for Economic Cooperation and Development) countries [7]. Germany is planning to reduce 20% of the total primary energy demand for buildings from 2008 level by 2020, and 80% by 2050, which requires increasing the rate of energy efficiency retrofits from the current 0.8% to 2.0% per year [8].

As for China, improvements in the standard of living lead by its rapidly growing economy have been demonstrated by a considerable housing boom. The growth rate keeps more than 10% per annum in the past 20 years in terms of building energy consumption [3]. In addition, only few of the buildings in China are energy efficient, which leads to a huge potential for the building retrofit market. For example, China plans to retrofit 150 million m^2 of existing buildings in the northern China by 2010 to achieve a 20% energy intensity reduction in the building sector [9]. Efforts toward a low-carbon society will make it inevitable to put building energy efficiency retrofits in a more and more important position in China.

From a global perspective, a double size worldwide market ($152 billion) for office building retrofits will appear by 2020 according to a recent report from Pike Research [10]. As is introduced in Chapter 1, in Europe public buildings account for 25% of the total stock. There are about 1,200 million square meters of floor space for office buildings [1]. the energy consumption levels falls into the range between 100 and 1000 kWh/m^2, and are relatively higher than the other building types [2]. For the past ten years the office building retrofit market in Germany has grown considerably. As for China, 34% of the total urban buildings are office buildings, but they consumed 56% of the energy for urban buildings (excluding district heating) [3]. The annual office building electricity use intensity varies between 30 and 300 kWh/m^2 (excluding district heating). In some cases, the office buildings have more than ten times of energy consumption than that of residential buildings [11]. Governments in northern China are promoting the insulation of residential buildings extensively. However for office buildings, governments are much less effective, even though retrofitting office buildings provides greater potential in energy savings.

2.1.1 Retrofitting office buildings and residential buildings: a comparison

Besides higher levels of energy consumption, differences between office buildings and residential buildings need to be addressed when discussing the retrofitting of office buildings. First, office buildings are usually more complex than residential buildings, and in many occasions it is difficult to identify an area to focus on. Retrofitting office buildings requires more efforts to understand the interactions between different building components for a satisfactory design. Second, the roles of the stakeholders cannot be neglected. For each office building, stakeholder requirements can vary widely. Retrofitting residential buildings is adequately investigated in both Germany and China, however retrofitting office buildings has not been assessed in depth. More efforts towards understanding the requirements are to be made. Third, a large part of energy-saving components have been developed for non-residential buildings. Compared with retrofitting a residential building, larger set of energy saving components tends to be investigated in retrofitting an office building. In this case, a satisfactory retrofit design is more complex to achieve for office buildings.

2.2 Challenges and opportunities

Although many EEMs (energy efficiency measures) are developed for buildings, the decision to select specific measures remain highly intuitive. Around 80% of EEMs are selected without taking alternative options into consideration [12]. Based on the background mentioned above, in order to help decision-makers to optimize and evaluate business and benefits, there is a need to embed decision support methodologies to enhance the efficiency of the selection and integration of EEMs for office building energy retrofits. However, obtaining optimal energy retrofit solutions is a challenging task. Typical challenges are seen in three aspects.

1. The selection and integration of EEMs is a relevant retrofit design decision problem that affects the future building performance with regard to embodied energy, operational energy, and other aspects like thermal comfort and environmental impact. A complete evaluation of building retrofits in the early design stage is quite difficult in that a building is often regarded as a complex system. A complex system is "*a system that can be analyzed into many components having relatively many relations among them, so that the behavior of each component depends on the behavior of others*" [13]. The interactions between different sub-systems and on the overall building performance (e.g., operational energy consumption, thermal comfort) are often quite detailed. In addition, the early design phase rarely provides detailed information on the potential improvements of building performance to design teams, hence leading to a situation

in which economic and design decisions must be made, but insufficient information is provided. However, these decisions will be essential for the later building performance (e.g., energy consumption, environmental impact, costs).

2. A building's energy efficiency retrofit solution is a compromise between stakeholder requirements (e.g., investment costs, thermal comfort, energy saving). For building retrofits, owners, tenants, designers, maintenance and operational teams, etc., are usually taken as the stakeholders. The problem is that they usually have fragmented expertise, varying, and in most cases conflicting requirements. As a results, it is rather challenging to integrate stakeholder requirements for satisfactory designs.

3. Nowadays an extensive set of EEMs has been developed. design teams have to take into consideration more and more potential EEMs for sustainable designs. In a retrofit project, there can be a lot of EEMs and a large quantity of combined solutions, which make it a hard problem to find the most adequate solution. On the other hand, introducing new energy efficiency technologies offers an opportunity to make better retrofit designs. However, stakeholders usually think that high-performance office buildings are less cost effective when there is no reasonable decision support. Hence, decision support is of great help to encourage the decision-makers to commit themselves to sustainable energy retrofits by understanding the opportunities offered by the latest energy efficiency technologies and learning how to best apply them.

Besides challenges, vast opportunities exist for improved building design integration whenever a retrofit project is being planned. It is widely recognized that decisions made in the early design phase have the biggest influences on building performance (see Figure 2.1 on the following page) [14]. The planning of retrofit projects is more challenging than that of newly-built projects. For building energy retrofit projects, tools that support decision-makers optimize and evaluate business and human benefits in the early design stage would be extremely valuable and marketable. In this study, the core research question is: *How can we develop a tool so that we can make informed decisions about energy efficiency solutions in the early design phase of office building retrofit where there is insufficient information?*

2.3 Current state of research

This section presents the critical findings from research in the field of decision support on building energy retrofits. The literature review will cover the following topics that are involved in the dissertation:

- Design decision support on the selection of energy efficiency measures.
- Conflicting stakeholder requirements.
- Processes of energy efficiency retrofits.
- Energy efficiency measures.
- Representative retrofit studies on office buildings.

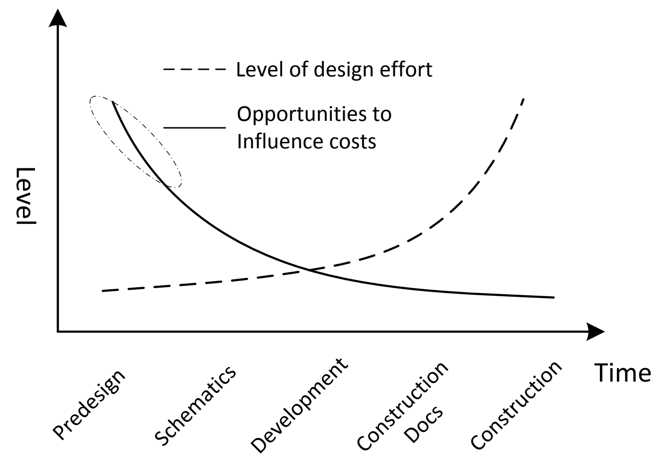


Figure 2.1: Opportunities to implement cost savings during the design-build process, adapted from [14]

2.3.1 Design decision support on the selection of energy efficiency measures

In the early design phase of a newly-built or an existing building retrofit project, the design teams have to choose a set of energy efficiency measures (EEMs) from a variety of potential EEMs. There are two primary approaches to selecting these measures in practice [15].

In the first approach, building performance is analyzed by building experts, and they will develop several alternative solutions for further evaluation with the help of building simulation programs [16]. Building simulation tools such as TRNSYS and EnergyPlus are employed to evaluate quality (e.g., energy performance, air quality) of the alternatives. The problem is, the trial-and-error searching process in this approach is normally ineffective and relies heavily on the designer's expertise and experience when exploring a large decision space of EEMs [17].

In the second approach, decision support techniques are employed in the design phase. These techniques include, but are not limited to cost-benefit evaluation approaches [7, 18], multiple criteria decision-making approaches [19–25], multiple objective optimization-based approaches [26–34], all of which have been applied to various circumstances. In this approach, the decision support techniques are usually combined with building related evaluation tools (e.g., energy simulation programs, environmental database) to select a solution among a set of alternatives.

Gero et al. [20] first applied a multi-criteria decision-making model for building design to deal with the conflicting objectives of building energy consumption, capital cost, and usable area. For the past 20 years, multi-criteria decision-making methods have been widely applied to solve building design problems. A number of multi-criteria based models have been developed to evaluate different retrofitting solutions [19, 21, 22, 35]. Alanne [24] applied a multi-criteria 'knapsack' model to select a set of activities in a building retrofit project. Wang et al. [25] developed a multi-criteria decision-making model based on fuzzy theory to deal with the uncertainty levels of qualitative criteria when selecting the optimal HVAC system during the design stage.

For new building designs and existing building retrofits, multi-objective optimization techniques have often been applied to optimize competing objectives and to evaluate the large sum of alternative options. There is no guarantee of finding optimal solutions if a large set of available measures are not evaluated simultaneously. Flager et al. [36] applied the multidisciplinary design optimization (MDO) to a classroom building design for the optimization of structural and energy performance. Geyer [37] applied a systematic and hierarchical design analysis with a MDO model to facilitate architectural design activities. Juan et al. [27] developed an optimization based decision support system to analyze the conflicts between costs and building quality. Chantrelle et al. [38] proposed a decision support system to evaluate the renovation measures and activities in terms of CO_2 emissions, investment cost, energy use and thermal comfort. Asadi et al. [29] proposed an optimization approach to evaluate and optimize the energy/cost saving objectives for a set of retrofit options. In their later research [39], a simulation-based MOO approach is proposed to optimize the retrofit cost, energy savings, and thermal comfort of a residential building. Hamdy et al. [40] implemented a three-phase simulation-based MOO approach to minimize the environmental impacts and costs for a house. Evins et al. [41] applied a design-of-experiments procedure for the screen of design variables before an optimization procedure. These works have proved that multi-objective applications are reliable when optimization approaches are well established. However, most of the researchers focused on the methods and applications of multi-objective optimizations, and objectives and constraints are usually assumed or pre-defined, which neglects the facts that for each building energy retrofit, the requirements can vary largely.

In these studies, many decision support problems of building retrofits have been addressed. However, it is important to fully explore the design possibilities by taking different facets of retrofits into consideration. The exploration includes a wide evaluation of potential EEMs, and then the definition and optimization of a large number of integrated retrofit solutions. In this process, many possible EEMs tend to be overlooked because of the cost situations, insufficient applications, and the lack of expertise of designers [42]. In addition, when incorporating the aforementioned mathematical optimization and evaluation techniques into the decision-making process, the important role of stakeholders must be considered simultaneously.

2.3.2 Conflicting stakeholder requirements

Satisfying the needs and expectations of the stakeholders is key to successful retrofit design. According to Miller and Buys [43], the lack of participation and cooperation among different stakeholders tends to lead to poor energy retrofit implementation. Stakeholders usually have multiple and in most of cases conflicting requirements. In addition, they usually have fragmented expertise [44]. De Wilde [4] presented an objective tree which shows design objectives (functions) in a diagrammatic form. Menassa et al. [45] listed 30 potential stakeholder requirements for retrofit projects. Kolokotsa et al. [17] noted that the criteria for energy efficiency retrofit fall into five categories (see Figure 2.2). Campos et al. [46] elaborated a list of criteria of retrofit scenario evaluation which belongs to four categories: benefits, opportunities, costs and risks.

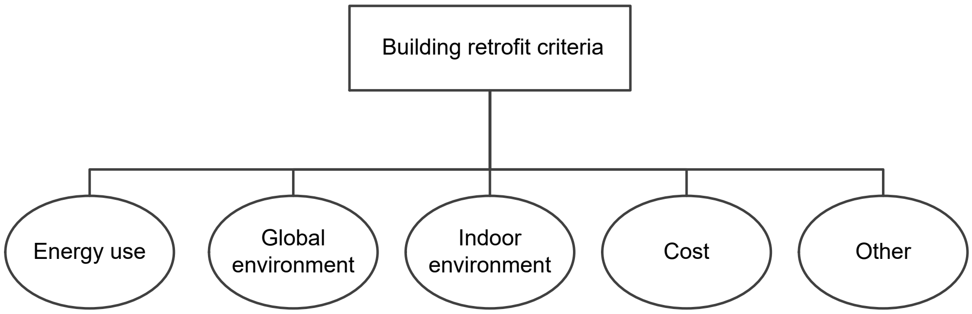


Figure 2.2: The main criteria for energy efficiency retrofit, compiled from [17]

According to Stephan et al. [47], conflicting stakeholder requirements is a big obstacle on the application of sustainable retrofit design. To mitigate this problem, a model has been established to analyze the social network interactions on prioritizing stakeholder requirements. Baer [48] developed a decision-making framework to understand the relationships between a list of requirements and the general technical considerations. The study also noted that conflicting stakeholder requirements hinder the development of sustainable retrofit projects.

Rey [19] concluded that when defining retrofitting strategies, many different goals (e.g., growth of building value, adaption to new standards) must be analyzed. In addition, stakeholders play important roles in the choice of potential options. For instance, a passive system trends to be avoided in buildings with air-conditioning devices and in buildings with different companies in them. Boecker et al. [49] indicated that the diversity of stakeholder requirements needs to be considered and managed in an integrative design process since the early phase. Lapinski et al. [50] noted in sustainable building projects, the early engagement of stakeholder collaboration must be emphasized, but in practice effective collaborations are hardly implemented.

Requirement analysis techniques are needed to address the specific requirements of a building retrofit project. Alanne [24] presented a tree-structured criteria model bassed on multi-criteria decision-making to select building renovation actions. Loh et al. [51] designed an assessment model to support the decision-making process of multiple stakeholders. An analytical hierarchy process (AHP) model is embedded in this tool to support trade-offs between different design criteria. Singhaputtangkul et al. [52] developed a knowledge-based decision support system to assess building envelopes. A quality function deployment (QFD) approach was applied to deal with the requirements of the stakeholders. It is proved that QFD has the potential to support early design decision-making processes.

In the existing research, requirement analysis techniques haven't been applied to identify the goals and constraints of retrofit design optimizations. More specifically, current design decision-support systems hardly or do not fully consider the important role of requirement analysis. However, it is clear that the success of an energy retrofit project is bound up with the stakeholder satisfaction level in terms of the project outcomes [53]. To aid the selection and integration of EEMs for energy retrofit solutions, this study will integrate requirement analysis based on existing methodologies into the whole approach.

2.3.3 Processes of energy efficiency retrofits

The British professional services firm Arup [54] introduced a comprehensive plan for the implementation of office building retrofits. The building retrofit process contains five major phases (see Figure 2.3). Ma et al. [7] presented an integrative methodology for sustainable building retrofits. It has two main parts: a planning and models selection part for retrofit preparation; and a decision support part for activities in the retrofit process.

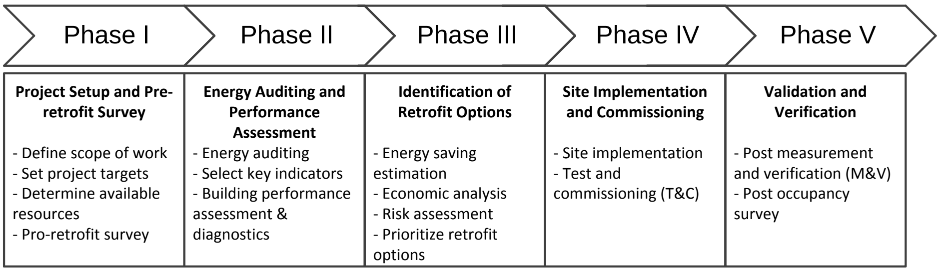


Figure 2.3: Key phases in a sustainable building retrofit programme, compiled from [7]

Several studies have shown that building information modeling (BIM) is a very useful tool during the process of retrofit, given that the physical and functional characteristics of buildings are managed in BIM to facilitate the development and evaluation of retrofit strategies. Laszlo [55] developed a new method for retrofitting public facilities using BIM and LCCA (Life Cycle Cost Analysis) systems by taking initial investment and the estimated future expenses into account. Schlueter and Thesseling [56] developed an integrated analysis tool by employing BIM in the early design stage that allows an immediate performance assessment of retrofit designs. A house is taken as a case study and it shows the integrated tool's ability to cope with the multiple dependencies between different aspects of the house.

With the development of BIM, the concept of integrated project delivery (IPD) [57] sees a continuing increase of its popularity. The IPD approach integrates people, business structures, and knowledge for effective collaboration and decision making in the AEC (architecture, engineering, and construction) industry. It is the goal of BIM implementation – to combine domain technologies, process and policies into one organization. Although at its very beginning, IPD shows a promising future for energy efficiency retrofit. Owen [58, 59] proposed a new approach to integrated design and delivery solutions (IDDS). IDDS take the concept of IPD together with BIM, it provides a framework for a holistic combination of the whole process and multidisciplinary participation in decision-making.

These lines of research have shown that a building energy retrofit is a complex process that consists of diverse activities, and multidisciplinary connections and participations. However, the processes of reaching a design solution among these studies have no guarantee that the proposed solution is well optimized. In this study, the new methodology is developed in a way that it is applicable in the context of an ongoing office building retrofit design process, especially for the early design stage. Stakeholder requirement analysis is integrated into an optimization and evaluation process of energy retrofit solutions. By doing so the EEMs will be screened and combinatorial optimized in accordance with the stakeholder requirements.

2.3.4 Energy efficiency measures

It is easy to understand that EEMs are building components that are designed to make buildings more energy-efficient. They are employed to minimize the energy needed by buildings, to access renewable energy sources, and to make more efficient use of fossil fuels. De Wilde listed most important main types of EEMs based on this classification. The three types of EEMs are explained as follows [4].

(1) Energy efficiency measures that minimize the energy needed by buildings. The energy consumption is mainly attributed to ventilation and infiltration, transmission, lighting and so on. Typical EEMs include thermal insulation, shading devices, low-e glazing layers etc.

(2) Energy efficiency measures that access renewable energy sources such as solar and wind energy. Typical EEMs include PV panels, skylights, wind turbines, ground source heat pumps, etc.

(3) Energy efficiency measures that make efficient use of fossil fuels. These EEMs are usually tied with heating, ventilation and air conditioning (HVAC) systems and office equipment. Typical EEMs include high-efficiency boilers, combined heat and power units, and building automatic control systems, etc.

Kolokotsa et al. [17] summarized the different actions for improving buildings' energy efficiency and classified these actions into 3 classes: building envelope and design aspects; building services; energy management tools. Ma et al. [7] categorized EEMs according to their positions in the whole energy supply chain: supply side management, demand side management, and energy efficient equipment.

For office building energy retrofits, EEMs are the fundamental components to deliver a satisfactory project. However the extensive set of EEMs cannot guarantee the success of retrofits. Many EEMs, especially new technologies, tend to be overlooked in retrofit projects due to the lack of reasonable decision support. It is the selection and integration of EEMs, which takes requirements, physical and functional characteristics, and business structures into consideration that affects the final result the most.

2.3.5 Representative retrofit studies on office buildings

Nowadays, office building retrofits are carried out extensively and a large quantity of case studies are available. Ma et al. [7] listed a wide range of related retrofit case studies. In this section, only additional representative retrofit case studies that applies innovative approaches or have notable significance are introduced.

Tobias et al. [60] explained some of the best sustainable office building retrofit practices. This guidance covers planning and managing sustainable office retrofits, the business of green office retrofits, and public policy for future sustainability. The practices demonstrate that sustainable building retrofit can be cost-effective.

Santamouris and Dascalaki [61] developed passive retrofitting strategies for office building in European countries. In the study, ten office buildings were investigated for potential retrofitting scenarios, aiming to promote cost-effective implementation of solar system and other EEMs. Balaras et al. [62] investigated the renovation of representative European office buildings by using the European TOBUS tool [22]. The implementation of TOBUS demonstrated its potential in identifying the actions required for sustainable retrofits.

The development of integrative design has lead to the implementation of deep energy retrofits on office buildings [63–65]. Deep retrofit is distinguished from the typical retrofit. The typical retrofit approach is to implement improvements measure-by-measure. For instance, a retrofit project may arise from an isolated glazing improvement when its outside windows are too old. The renovation of outer walls is among the most popular typical building retrofits in both Germany and China [66, 67]. Deep energy retrofit requires integrated design by taking the advantage of interactions between building components. By doing this, the retrofit is carried out more deeply, and a higher level of energy saving is achieved. Olgyay and Seruto [63] noted that deeper building retrofits must be designed to achieve the full potential in carbon emissions reductions. Zhai et al. [65] introduced an four-step approach to deep office building energy retrofits. The study showed that deep retrofit is better than the conventional retrofit effort in terms of energy saving.

2.3.6 Summary of the literature review

The studies above have shown that the selection and integration of EEMs are of great importance for the success of office building energy retrofits. From the literature review, several aspects must be improved in this research:

• It is important to fully explore the design possibilities by taking different facets of retrofits into consideration. The exploration includes a wide evaluation of potential EEMs, and then the definition and optimization of a large number of integrated retrofit solutions.

• In the current state-of-art studies, requirement analysis techniques haven't been applied to identify the goals and constraints of retrofit design optimizations. More specifically, current design decision-support systems hardly or do not fully consider the important role of requirement analysis.

• Retrofitting office building consists of diverse activities, and multidisciplinary connections and participations. However, the processes of reaching a design solution among these studies have no guarantee that the proposed solution is well optimized.

• Many EEMs, especially new technologies, tend to be overlooked in retrofit projects due to the lack of reasonable decision support. It is the selection and integration of EEMs, which takes requirements, physical and functional characteristics, and business structures into consideration that affects the final result the most.

In conclusion, there is a need to integrate requirement analysis, optimization and evaluation techniques to propose optimal building retrofit solutions in the early design phase. In this study, the development of a systematic approach for energy retrofit solutions for existing office buildings will be based on these critical findings. The strengths of these findings will be fully employed, and weaknesses will be avoided and improved.

2.4 Problem definition

With the development of building solutions and technologies, in order to achieve a satisfactory energy retrofit design, the design team has to take more and more EEMs into consideration, and there are more than 400 different EEMs that could be undertaken [68]. However as is discussed in Section 2.2 on page 6, the decision to select a specific measure remains highly intuitive, around 80% of EEMs are selected without considering alternatives [12].On the other hand, successful energy efficiency retrofit solutions also relate to the achievement of stakeholder satisfaction and the optimization of the total value of a project design. A building's energy retrofit solution is a compromise between several stakeholder requirements (e.g., investment costs, thermal comfort, energy saving). The stakeholders usually have fragmented expertise, and varying and, in most cases, conflicting requirements [5]. The question of how to integrate these stakeholder requirements and find a consensus among the stakeholders is quite challenging.

Therefore, this study will present a new decision support methodology to help the designers to make informed decisions on choosing the most appropriate EEMs for retrofitting office buildings with a compromise of stakeholders' diverse and often conflicting requirements.

In particular, the doctoral research will show the following:

1- In a building energy retrofit project, actual objectives, constraints and requirements are frequently linked to actual design options, and they need to be defined and quantified with the help of proper requirement engineering tools in order to find optimal solutions.

2- The traditional process of trail-and-error process among a set of predefined alternative solutions is not enough. Instead, optimal/near-optimal trade-offs that satisfy the stakeholders requirements are to be generated from a large range of potential EEMs with the application of optimization approaches.

3- The evaluation of alternative solutions needs to be determined by the stakeholders' criteria and constraints. The nature of the problem makes multiple criteria decision analysis a prefect tool for evaluating the alternatives.

4- Real-world construction activities do not behave in a deterministic manner, and most systems behave stochastically — involving variation or probability. Thus, uncertainty analysis is needed to address the design uncertainties and to investigate the reliability and robustness of design solutions.

5- The ultimate goal of the doctoral research is to develop a validated model for the improvements of the performance of office buildings with regards to energy consumption and energy savings, environmental impact, indoor environment and costs.

The new methodology will be developed to a certain extent as it was previously discussed. This research model and its databases include information based on limited national data from selected countries. However, the methodology can also be adapted to other types of buildings and other countries. Since building characteristics, costs and EEMs change from country to country, the adaptation not only consists of simple translation, but it has to take into account the domestic reality (e.g., climate, economy, technologies, materials) and building types.

2.5 Conclusion

Retrofitting existing office buildings for energy efficiency and sustainability is of great importance. Nowadays an extensive set of EEMs is found on the market and design teams have to compromise between stakeholders' diverse and often conflicting requirements in order to find a satisfactory solution. A systematic approach to energy retrofit solutions of existing office buildings is linked with energy efficiency measures, retrofit design, building performance simulation, design optimization, decision support and assessment, and analysis methods. These areas of research have allowed many problems of buildings retrofit optimization to be addressed. However, the analysis shows that requirement analysis is often neglected or not connected to the optimization tools without a structured interaction with the design team, and the evaluation of the design solutions is often neglected.

Consequently, a systematic approach to energy efficiency retrofit solutions for existing office buildings is needed. A new methodology to support the selection and integration of office building's EEMs with respect to multiple stakeholder requirements is described in the following chapter.

Chapter 3

Development of the methodology with an illustrative case study

This chapter addresses the research problem statement by proposing a systematic approach to energy efficiency retrofit solutions for existing office buildings. To achieve this, a model-based method that supports design teams for energy retrofit solutions in the early design phase is established. The new methodology connects the multiple and in most cases competing objectives with the large number of potential energy efficiency measures. A framework is applied that includes requirement analysis techniques to identify and quantify stakeholders' concerns and needs. In the optimization stages, the building performance assessment model consists of different modules to calculate the numerical indicators in terms of the selected design criteria. The methodology combines these approaches and is applied to buildings as a whole. Through the integrated approach, the methodology supports the selection and integration of energy efficiency measures with respect to multiple criteria and constraints.

The methodology is applied for an illustrative case study in Germany along with the development of the new approach to explain the whole work process. The application of the methodology will be fully explored by taking an existing office building in northern China as a detailed case study in Chapter 4.

3.1 Introduction

The previous chapter illustrated the importance of developing a systematic approach to energy retrofit solutions for existing office building. Of particular note is that stakeholder requirements and the large range of energy efficiency measures (EEMs) should be addressed in a holistic manner. The new methodology is thus developed and introduced in this chapter. A general structure of the methodology is illustrated in Section 3.2 on the following page, it can be seen that the whole work process and application contain three main parts and they are discussed in detail in Section 3.4 on page 21, Section 3.5 on page 28, and Section 3.6 on page 34. The functionality of the proposed methodology will remain abstract without an illustrative example.

In this chapter a case study is introduced to demonstrate the use of the model.

The term ‘optimization’ is interpreted in two ways depending on its context in this thesis. When it is used in mathematical programming (e.g., multi-objective optimization), it means selecting the best element(s) among available alternatives by applying mathematical algorithms with objective functions [69]. In addition to that, in architectural design it also represents the process of manually adjusting a system to improve the quality or efficiency [70].

3.2 General Structure

The general structure of the methodology is illustrated as an activity diagram [71] to trace the work flows (Figure 3.1 on the facing page) [72]. The basic idea behind the structure is allowing the design teams to specify the optimum retrofitting solutions with regard to the diverse requirements of stakeholders. The methodology contains an analysis procedure to be carried out by the design team and a numerical procedure of optimization carried out by computer. The analysis procedure, which contains a quality function deployment model, allows the design team to identify and quantify stakeholders’ concerns and needs in order to set up the optimization model according to the characters of the building. The analysis procedure leads to a modular analysis and optimization model including the objectives and constraints from the design team results as inputs. Subsequently, an automated procedure explores this model by multi-criteria constrained optimization to deliver information on the design space. The model provides a basis for embedding quality function deployment and multi-objective optimization into the decision making on energy efficiency retrofit solutions, which considers the important role of the design team by carrying out the analysis procedure.

It is important to mention that the new methodology is still limited to research purpose, and an integrated computer-based tool with a user-friendly interface between the model and the users is not implemented in this study. The methodology was developed mainly based on Enterprise Architect [73], Matlab [74], Isight and SIMULIA Execution Engine (courtesy of Beihang University) [75], and Microsoft Excel [76].

As was discussed in Section 2.3.3 on page 11, although there are different processes of retrofitting office building, the whole design process normally consists of an early design phase and a detailed design phase. Take office buildings in Germany as an example, according to German HOAI (Official Scale of Fees for Services of Architects and Engineers) [77], there are nine phases of architectural services (Figure 3.3 on page 20). Phase 1 and 2 include the collection of basic information and preliminary design, where the proposed methodology can be applied.

To apply the methodology in a comprehensive manner, the interactions between different stakeholders are of great importance (Figure 3.3 on page 20). The new methodology, as a decision support system, serves as the central hub for communications. During the interactions, stakeholder requirements are analyzed. Hence the design team needs to master the requirement analysis techniques in the methodology. In addition, the design team needs to teach

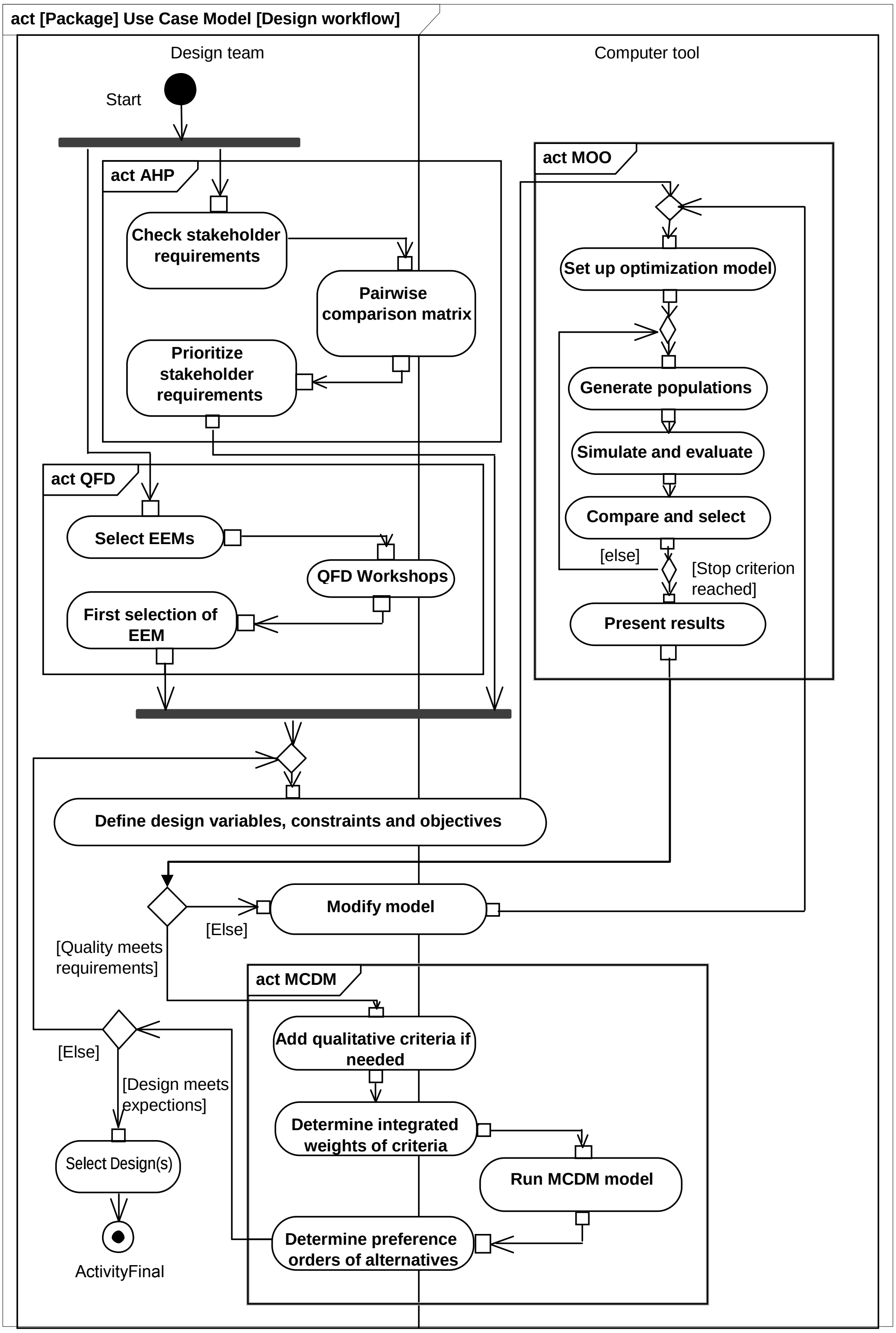


Figure 3.1: The activity diagram of the methodology serves to trace the design process and optimization activities. AHP represents analytical hierarchy process; QFD represents quality function deployment; MOO represents multi-objective optimization; MCDM represents multi-criteria decision-making.

Development	Building Design / Planning Phase					Construction / Realisation Phase			Operation
	1	2	3	4	5	6	7	8	9	
Step	Investigations of Basics	Schematic Design	Design Development	Building Documents	Executive Design	Mass Records and Advertising	Negotiation and Contracting	Construction Supervision	Building Documentation	Step
Fee	3%	7%	11%	6%	25%	10%	4%	31%	3%	100%

Figure 3.2: HOAI: nine phases of architectural services, reprint from [77]

stakeholders on how to apply the pairwise comparison matrix to prioritize their requirements.

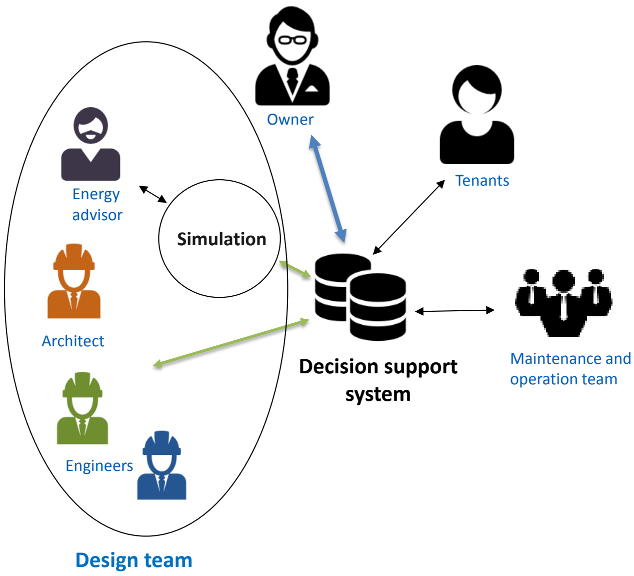


Figure 3.3: Interactions between different stakeholders in the methodology

3.3 Case building as an illustrative example

In this section, an office building from Aachen, Germany (see Figure 3.4) is taken as a case study. It was built in 1900, and the poorly insulated façade, low-efficiency lighting system, and obsolete heating system lead to a high primary annual energy demand up to 605 kWh/m^2 and a total energy demand of 540 kWh/m^2 per annum, which are much higher than the reference values for existing non-residential buildings defined in EnEV 2014. The basic information for this building is shown in Table 3.1 on the next page.

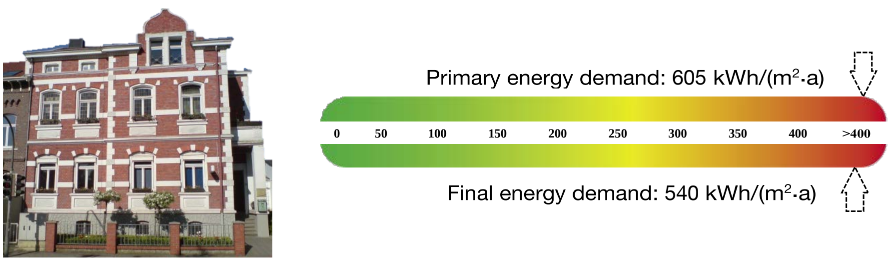


Figure 3.4: The office building in Aachen and its energy performance label.

Table 3.1: Basic information on the case study, adapted from Meyer [78].

General building data	Building use	Office and administration
	Year of construction	1900
	Heated floor space	400 m^2
	Net volume	978 m^3
	Gross volume	1450 m^3
	Inner ceiling height	Ground Floor: 3.40 m; Basement: 2.08 m; Typical Floor: 3.16 m; Attic: 2.60 m
Building elements	Attic and roof	Heated; Gabled roof, $45°$ pitch; Wood construction; U-value: 2.60 W/m^{2}K; Roof area: 168 m^2
	Exterior walls	Massive construction; Area: 327 m^2; U-value: 1.70 W/m^{2}K
	Basement	Unheated; Basement ceiling area: 117 m^2; U-value: 1.20 W/m^{2}K
	Windows	Wooden frame; Single-glazed; Window area: 54 m^2; U-value: 5.00 W/m^{2}K
	Sun shading device	Partially blinds on the ground floor
	Heating system	Central gas-fired boiler, 72 kW, installed in 1982; Heating control: constant temperature 90/70℃, external temperature control with setback; Located in unheated space; Insulation of heating pipes: under the basement ceiling with 0.2 W/mK
	Lighting system	Illumination lamp: directly and indirectly; Illuminant: fluorescent lamp; Ballast: conventional; Power: 25.5 W/m^2

3.4 Design analysis

This section explains the details of the design analysis, the first step of the new approach, and illustrates how this step can be used to provide support for requirement analysis and screening potential EEMs. This step corresponds to 'act AHP' and 'act QFD' in Figure 3.1 on page 19. As discussed in the previous chapter, successful energy efficiency retrofit solutions require achievement of both stakeholder satisfaction and the optimal total value of a project design. To this end, this section deals with identifying stakeholder requirements (e.g., capital cost, energy consumption, environmental impact), potential EEMs (e.g., heat pumps, advanced glazing systems, thermal insulation layers) and the related design variables as well.

Dealing with energy retrofit design optimization of existing buildings is rather complicated. One of the reasons is that retrofit solutions have to fit into an existing context, which requires strong interaction with users and society. Of particular note is that besides quantifiable design criteria, other qualitative criteria (e.g., appearance, spatial quality) are also important for the success of a retrofit project. However these criteria require the assessment from designers and planners, and it is not part of the methodology due to the limitations of the integrated numerical optimization stage in the methodology. This study proposes a multi-criteria decision making (MCMD) process (Chapter 5), in which only a preliminary analysis on qualitative criteria can be carried out. The expertise and experience of designers and planners remain essential in analyzing the qualitative criteria.

3.4.1 Stakeholder requirements

It is obvious that one of the main goals of an energy efficiency retrofit is to make office buildings more energy efficient. However, energy efficiency is only one of the many requirements that need to be considered. Other requirements, such as low carbon emissions and low investment costs, may also need to be considered.

According to Singhaputtangkul et al. [52], "*inadequate consideration of requirements in the early design stage is a major cause of poor performance of construction projects*". As discussed in the previous chapter, in most design projects, the clients only provide general needs and wishes. Actual objectives, constraints, and requirements are frequently linked to actual design options and hence need to be defined during the course of the design process. Each building is unique with different characteristics and different customer preferences, so the selection of criteria relies on the context at hand.

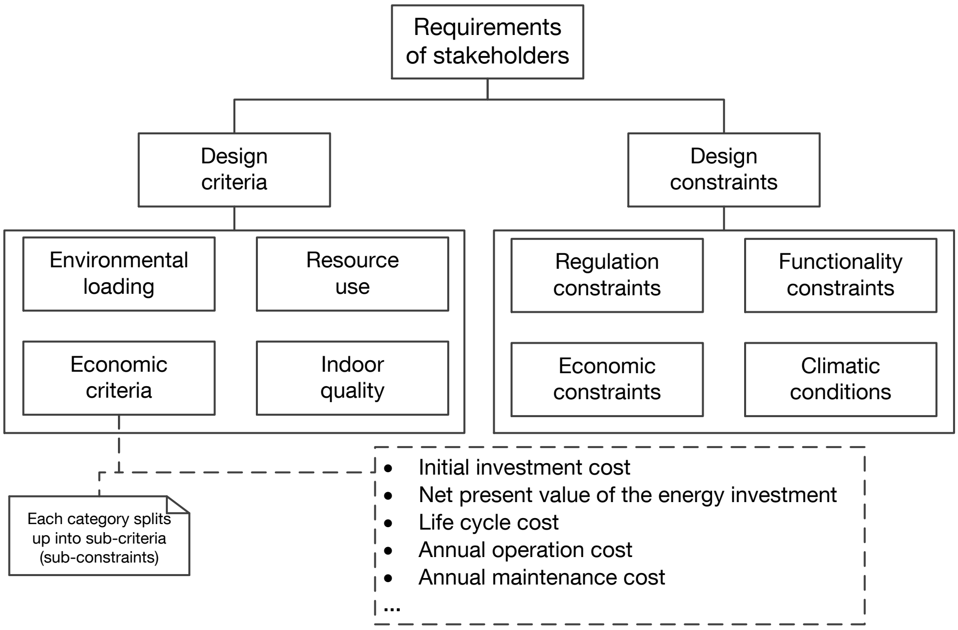


Figure 3.5: The hierarchical structure of stakeholder requirements.

General requirements like resource use and environmental impact can be used in the early design stage. In order to support the design teams in identifying the specific stakeholder requirements, a hierarchical structure of the requirements is established (Figure 3.5) containing an overview of different performance indicators that are used to quantify given performance aspects. This requirement tree could be applied to support the definition of the criteria and constraints.

Stakeholder requirements belong to two main categories: criteria and constraints. Criteria measure the matching objectives in design optimization problems. It is stated that the following requirements should be meet when defining the criteria [79]: systemic, consistency, independency, measurability, and comparability. The category of design criteria has four groups. The first group contains economic criteria, the second resource use, the third environmental loading, and the forth group is indoor quality. Each group consists of sub-criteria that can be measured by the matching indicators. Design constraints are the functions that come with the values that must be met in order for the design to be acceptable. These design constraints are subjected to regulation constraints, functionality constraints, economic constraints and climatic conditions, with each of them containing several sub-constraints. The design criteria and constraints are transformable to each other depending on the actual model development at the beginning. It should be noted that climatic conditions must be integrated into the design process as the location of a building plays a large role in its building performance.

To define the design criteria and constraints, a pairwise comparison matrix between the requirements is established. A pairwise comparison matrix is often used in an analytical hierarchy process (AHP) as the first step to compute or determine the weights of the different criteria. A square matrix $A(m \times m)$ is used to represent the pairwise comparison matrix, where m represents the number of the design criteria. In the matrix a_{ij} is the relative importance of the ith criterion compared to the jth criterion. The ith criterion is more important than the jth when $a_{ij} > 1$. Two criteria have the same importance if $a_{ij} = 1$, and a_{ij} and a_{ji} meet the following equation:

$$a_{ij} \times a_{ji} = 1 \tag{3.1}$$

The pairwise comparison matrix A is expressed as follows [80]:

$$A = \begin{array}{c c} \text{criteria} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_m \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_m \end{array} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mm} \end{pmatrix} \end{array} \tag{3.2}$$

The pairwise comparison matrix part of AHP is employed in this process. The discussion of AHP is beyond the scope of this chapter and will be found in Chapter 5 on page 77. As for design constraints, they are defined according to the actual conditions because constraints are compulsory in most cases. A constraint that is not compulsory, which is called a soft constraint, is usually translated into a variable value that is penalized in the objective functions [81]. Typically, defining criteria and constraints are done through interactions and collaborations between the owner, the design team, and the facility users In order to save the computation effort in the numerical optimization process, and to avoid overlapping optimizations, it is recommended that the number of the selected criteria is constrained to no more than four.

For the case building, an AHP pairwise comparison matrix of the requirement checklist is conducted first by the design team to define the design criteria and constraints. Results show that the three selected criteria are the initial investment cost (R_1), the annual operational energy consumption (R_2), and the global-warming potential (GWP) effected by the annual CO_2 equivalent emissions and the embodied emissions (R_3).

Table 3.2: Pairwise comparison matrix to identify the relative importance of stakeholder requirements. The relative priority of requirement R_i to R_j has a score of 9 if R_i is much more important than R_j. In contrast, the relative priority of R_j to R_i is much less important, which has a score of 1/9 (0.111). Other levels of relative priority are: more important with a score of 3, the same with a score of 1, less important with a score of 1/3 (0.333). The users will make their preferences based on the scale and obtain priority rankings of the requirements with respect to the overall scores on the right column.

=Much More Important	=More Important	The =Same	=Less Important	=MuchLess Important
9	3	1	1/3	1/9

	Initial investment cost	Annual operational energy	Annual emissions GWP	Embodied energy	Net present value	Life cycle cost	Annual fuels		
	1	2	3	4	5	6	7	Total	in %
1	X	2.00	2.00	5.00	2.00	2.00	5.00	18.00	28
2	0.50	X	2.00	5.00	2.00	2.00	3.00	14.50	22
3	0.50	0.50	X	5.00	1.00	1.00	3.00	11.00	17
4	0.20	0.20	0.20	X	0.30	0.30	0.50	1.70	3
5	0.50	0.50	1.00	3.33	X	1.50	2.00	8.83	14
6	0.50	0.50	1.00	3.33	0.67	X	1.00	7.00	11
7	0.20	0.33	0.33	2.00	0.50	1.00	X	4.37	7

3.4.2 Energy efficiency measures and design space

Retrofitting an office building to be energy efficient relies on the utilization of EEMs, whilst the requirements and conditions of buildings differ from one another and not all EEMs work well in every situation for every building. In an energy retrofit project, the first step in design optimization is to identify which EEMs are to be considered. The set that contains all potential EEMs is named the design space. To provide support for the identification of a design space, one possibility is to develop an ontology of EEMs in the form of a hierarchical structure that contains an overview of building EEMs and a set of relevant design-dependent and design-independent parameters [12, 82]. The structure of EEMs is split up into four major groups which respectively comprise EEMs that aim to improve: (i) building envelopes; (ii) building services; (iii) building management systems; (iv) sustainable energy options. The relevant parameters are the EEM properties and how they affect each design requirement. In this manner, the design team can have easy access to each EEM and evaluate how it will satisfy the design requirements, helping to speed up the definition of the design space.

To reduce the scope of possible options, several general requirements need to be met when the design team chooses potential options within the model. The options should: (i) be capable of reducing energy needs or utilizing renewable energy for buildings; (ii) be commercially available; (iii) be technically feasible (e.g. utilization of water or ground source heat pump where there is rich and stable geothermal energy); (iv) meet the local climate conditions; (v) be considered acceptable for stakeholders. The selected EEMs will be filled into the QFD model explained below together with the requirements to define their correlations and the priorities of EEMs.

3.4.3 Development of the quality function deployment (QFD) tool

Satisfying the needs and expectations of the customers is one of the most important goal for organizations in any industry. With this aim, many tools have been developed and adopted. QFD is regarded as highly effective, which systematically deals with the customer requirements and the engineering characteristics of the design by linking them together.

QFD is a "*method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process*" [83]. It can be applied as "*a set of planning and communication routines that focuses and coordinates skills within an organization to design and construct facilities that satisfy the client's needs*" [84] in building construction. The whole process is driven by the main tool house of quality (HoQ), whose name is derived from its house-like appearance, using a matrix that connects customer requirements with different options, and lists the importance. Therefore designers can determine which characteristics are more important. A basic HoQ contains 6 parts as shown in Figure 3.6 on the next page. 'Customer Requirements' and 'Customer Importance Rating' contain a list of customer needs and its importance, respectively. The 'Design Options' part contains the potential design alternatives, while the 'Correlation Matrix', which is not used in this study, defines their relationships with each other. The 'Relationship Matrix', which is the heart of HoQ, can help the design team to conduct a quick link between identification of relevant functions and the way these functions will be quantified. The 'Assessment Results' part sums the importance of each design option and presents the prioritized options. Filling in the matrix parts helps the decision-makers to understand a series of questions regarding design targets and engineering options (e.g., "how does the fulfillment of one requirement support that of another" for correlation).

In order to implement QFD in the design analysis procedure, the general QFD structure needs minor revisions. In the first place, the name of each part is supposed to be changed to represent its application in building retrofit designs. Second, stakeholders' requirements are to be divided into two parts: 'criteria' and 'constraints'; Third, the 'Customer Importance Rating' part responses to the part of 'criteria'. In this study, a new QFD-based approach that supports decision-making on energy efficiency retrofits is developed (Figure 3.7 on page 27). This tailored QFD table has five major parts, which are 'Part 1' (stakeholder requirements), 'Part 2' (EEMs), 'Part 3' (relationship between stakeholder requirements and EEMs), 'Part 4' (importance of stakeholder requirements), and 'Part 5' (assessment results). Part 1 and Part 2 are for the identification of the potential design criteria and constraints, and alternative EEMs. 'Part 3' shows the connections between the design criteria (constraints) and the alternative EEMs.

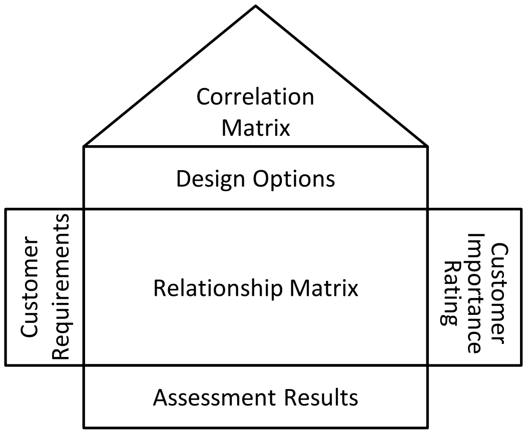


Figure 3.6: The basic structure of the house of quality table.

'Part 4' records the weight factors of the selected design criteria, whilst 'Part 5' records the selected design variables of EEMs. The relationship matrix shown as 'Part 3', is determined by the design team based on the ontology of EEMs explained in Section 3.4.2.

The design team only needs a little effort to master the tailored QFD matrix. In a retrofit project, a workshop which focuses on applying QFD is run to flush out stakeholder requirements and design options, and to help the entire team understand the issues surrounding the project. The first step of applying QFD for a retrofit design is to take the full list of stakeholder requirements as the input. The aforementioned 'act AHP' (see Figure 3.1 on page 19) is applied to formulate the list and determine the critical items that are included by collecting and analyzing data from stakeholders, while the constraints are derived from the project conditions. At this point, 'Part 1' and 'Part 4' in the matrix are in place. Then the design team will determine the potential EEMs for evaluation with the help of the checking list introduced in Section 3.4.2, so 'Part 2' is to be filled. Now that 'Part 1' and 'Part 2' of the matrix are in place, the third step is to determine their relationship in 'Part 3'. An entry in this part is multiplied by the weight of the design criterion. After calculating such number for each entry, total numbers for the correlation are derived. Note that in a retrofit project, the energy audit results may show some retrofits that are highly recommended or must be made, and these facts will be reflected in the planning of retrofit design, too. In the tailored QFD table, these factors are classified into design constraints so as to put a dominate priority of certain EEMs. For instance, if the external wall of an office building has a poor thermal performance and fails the regulation, then insulating the external wall will be considered as a dominating option. Finally, the sum of relative importance of each EEM that was just calculated in 'Part 3' is taken and entered in 'Part 5'. A high weighted sum of a EEM means that the EEM is recommended to be selected. The user can then select the most important properties as a base for the next stage of development. The QFD model could be applied by the design team and the stakeholders multiple times, and a final result is a comprehensive compromise among stakeholders' analysis.

A QFD model is established for the case building to determine the relationships between the EEMs and the requirements and to screen the potential EEMs (Table 3.3). The weight

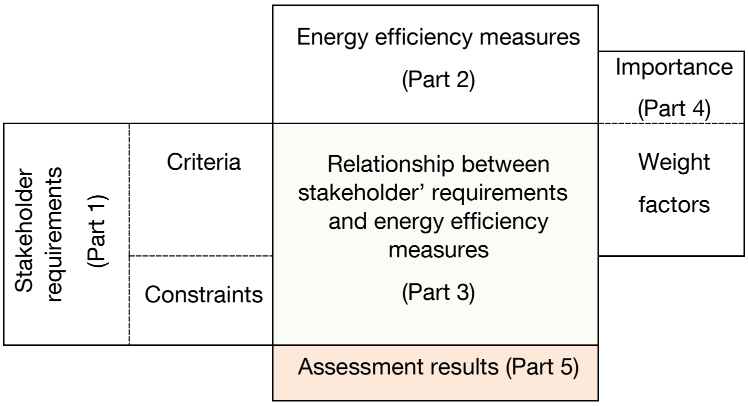


Figure 3.7: The planning of quality function deployment (QFD) for retrofit design.

factors of the EEMs vary between -5 and 5, rating their relationships with each design criterion. A bigger positive value means a stronger correlation, while a bigger negative value means a stronger negative correlation. The final weighted sum of each EEM is calculated by multiplying its weight factor by the weight factor of each criterion and adding them together. The constraints help to identify the dominate priorities of certain EEMs.

Table 3.3: Quality function deployment (QFD) analysis for the office building case study in Aachen, Germany. A negative number means that an energy efficiency measure (EEM) has an adverse effect on a criterion, and a positive number is given for a positive effect. The design team left several blank spaces for 'annual emissions GWP' because there are trade-offs between the EEMs' embodied carbon emissions and the annual carbon emissions saved due to their implementations, but the effects are hard to estimate. The mark '×' for constraints means a compulsory selection of an EEM due to the constraint.

Criteria and Constraints	Direction of improvements	Insulate external walls	Insulate roofs / attics	Insulate floor	Renewable insulaton materials	Improve building tightness	Glazing insulation	Advanced envelope technologies	Heating/cooling system	Building automation system	Photovoltaic (PV)	Weight factor	Weight factor %
Initial investment cost	Minimize	-2	-2	-2	-5	-2	-2	-5	-2	-5	-5	5	42
Annual operational energy	Minimize	5	5	5	5	2	5	5	2	2	2	4	33
Annual emissions GWP	Minimize				2	2	-2		2	2	2	3	25
Envelope physical values	Constraint	×	×	×			×						
Annual energy consumption	Constraint												
Envelope air leakage	Constraint					×							
Indoor air quality & thermal comfort	Constraint												
Climate	Condition	×	×						×				
Weighted sum		10	10	-2	1	6	12	-5	4	-11	-11		
Selected EEMs (×)		×	×	×	×	×	×		×				

Within this section, the stakeholders' concerns and needs are identified and quantified, potential EEMs are identified, and the constraints are defined along with this process as well. It is important to remember that expert knowledge and expertise regarding the design under development remain essential to success, since only experts in the field will be able to develop a design space that contains the relevant and most promising design options.

3.5 Multi-objective optimization

3.5.1 Principles of multi-objective optimization

In this study, the selection and integration of EEMs to formulate optimal solutions is regarded as an MOO problem. In general, the mathematical expression of MOO problems is shown as follows [85]:

$$\begin{aligned} &\text{minimize } f_i(x),\ i = 1, \ldots, N_{obj}. \\ &\text{subject to } g_j(x) = 0,\ j = 1, \ldots, M_{eq}. \\ &\qquad\qquad h_k(x) \leq 0,\ k = 1, \ldots, M_{ineq}. \end{aligned} \tag{3.3}$$

where f_i is the function for the design objectives, x is a design variable vector which represents a solution, N_{obj}, M_{eq} , and M_{ineq} represent the number of objectives, equality / inequality constraints, respectively. Here all objective functions are transferred minimization type, because a maximization type function can be easily converted to a minimization type.

Implementing the methods of optimization relies on the successful translation of a retrofit project at hand with its characteristics, design criteria, constraints, and design space into this formula. As stated previously, the objective functions often compete with each other in building retrofits. In most cases a set of optimal solution will be generated due to such competing objectives. In this situation, there is no solution that is better than the rest solutions with respect to all objectives. The set is defined as Pareto optimal solutions (Figure 3.8 on the next page).

In a multi-objective optimization problem where the objective functions are of the minimization type, a solution x_1 dominates or covers another solution x_2, when they meet the following requirements [85]:

$$\forall i \in \{1, \ldots, N_{obj}\} :\ f_i(x_1) \leq f_i(x_2) \tag{3.4}$$

$$\exists j \in \{1, \ldots, N_{obj}\} :\ f_j(x_1) < f_j(x_2) \tag{3.5}$$

In this study, the chosen MOO method is non-dominant sorting genetic algorithm-II (NSGA-II) [86], an evolutionary algorithm to generate Pareto optimal solutions. NSGA-II shows its efficiency and reliability in architecture optimization problems [38, 87, 88]. The MOO approach is combined with a building performance assessment model (Figure 3.9 on the facing page). An interactive cycle between the optimizer and the building performance assessment model is developed, where the optimizer sends the values of design variable to the building performance model. The model is then executed with these values, the results, known as the objective val-

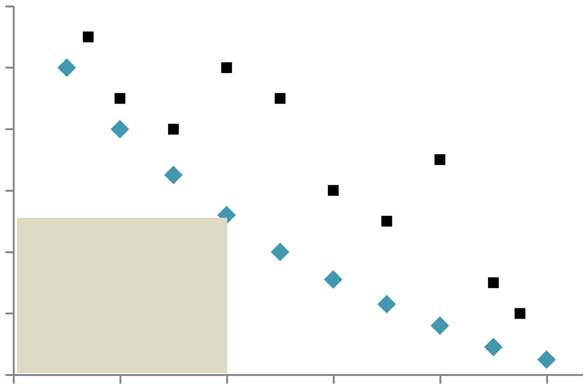


Figure 3.8: Pareto front example: diamonds represent Pareto optimal solutions for the minimization of two objectives.

ues, are sent back to the optimizer, which compare the new values with previous permutations of the variables. By optimizing the objectives and taking the constraints into consideration simultaneously, the optimization model generates a set of optimal retrofit solutions that can be evaluated by the design team with a higher level of information to choose one of the obtained solutions.

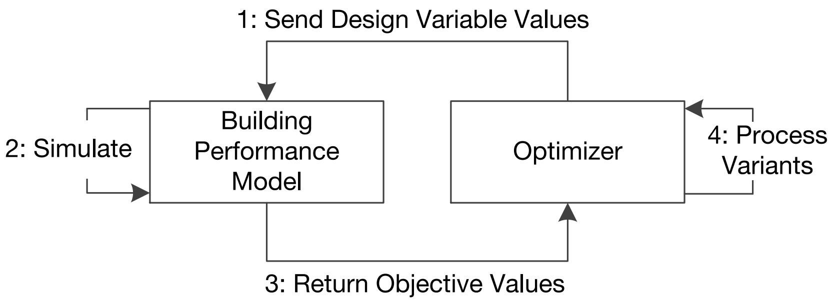


Figure 3.9: The optimization process with an interactive cycle between the optimizer and the building performance assessment model.

3.5.2 Design variables and design space

The retrofit solutions in this study concern a combination of choices regarding various EEMs. A design variable thus represents the alternative choices of a chosen EEM. Once alternative EEMs are identified, the design team then defines the design variables accordingly. Each design variable will have a feasible region. For instance, a design team will define a set of external wall insulations with different properties (e.g., insulation material, thickness, and cost). The design variables with their feasible regions comprise the design space that will be explored in the MOO model.

Here the amount of design variables isn't necessarily equal to the amount of the EEMs selected from the QFD model. First, some options such as sustainable insulation materials are complementary features of another chosen option(s). Second, some options may only have one choice, and it is in the QFD matrix where the choice is selected or not, so there is no need to define it as a design variable for further evaluation. For example, the ‘sustainable insulation materials’ option is a complement of the insulation options to explore the possibility of enhancing building sustainability. The current study considers six design variables for the case building: insulation types of the external walls, the roof, and the floor, window types, building tightness, and heating systems. Tables 3.4 to 3.9 on pages 30–32 present the six design variables and their properties. Sixteen insulation types for the external walls are described in Table 3.4. Fifteen insulation types for the roof are described in Table 3.5. Table 3.6 presents thirteen insulation types for the floor. Four types of windows are shown in Table 3.7, in which the embodied GWP is calculated based on the Beacon report [89].The options of building tightness improvements are shown in Table 3.8. Five types of heating systems are shown in Table 3.9.

The list of alternative EEMs shown in Tables 3.4 to 3.9 is based on the LEGEP database [90] extracted by the authors and a short market survey. The GWP data were from the Ecoinvent life-cycle database [91], and the chosen life cycle impact assessment (LCIA) method from the IPCC (Intergovernmental Panel on Climate Change) 2007 impact assessment method [92]. The transportation emissions on GWP are not taken into consideration.

Table 3.4: Characteristics of external wall insulation materials

N	Insulation types	Thickness (mm)	U-value (W/m^{2}K)	Cost (€/m^2)	GWP (kg CO_2-eq/m^2)
0	XPS (Extruded Polystyrene)	80	0.348	40.5	8.1
1		100	0.29	43.6	10.1
2		120	0.249	46.7	12.1
3		140	0.218	50.6	14.2
4		160	0.194	56.6	16.2
5		180	0.174	66.3	18.2
6	EPS (Expanded Polystyrene)	80	0.356	37.3	6.5
7		100	0.297	39.6	8.2
8		120	0.255	42.3	9.8
9		140	0.223	44.7	11.5
10		160	0.199	47.1	13.1
11		180	0.179	49.9	14.7
12	Vacuum Insulation Panel	20	0.29	190.5	8.1
13		25	0.24	209.6	10.1
14		30	0.205	227.4	12.2
15		40	0.159	293.9	16.2

3.5.3 Objective functions and constraint functions

The objectives in design optimization problems are measured by the matching criteria. In the first step, the relevant criteria and constraints have been identified by the QFD-based tool, and then the corresponding performance indicators and numerical qualifications are defined by the design team to represent the criteria and constraints in the design optimization algorithm.

Table 3.5: Characteristics of sloped roof insulation materials.

N	Insulation types	Thickness (mm)	U-value (W/m^{2}K)	Cost (€/m^2)	GWP (kg CO_2-eq/m^2)
0	EPS	100	0.35	55.7	8.2
1		120	0.301	58.2	9.8
2		140	0.262	60.7	11.5
3		160	0.228	63.4	13.1
4		180	0.205	63.9	14.7
5	XPS	100	0.331	61.1	10.1
6		120	0.28	64.3	12.1
7		140	0.246	68.4	14.2
8		160	0.218	74.4	16.2
9		180	0.2	84.1	18.2
10	Sheep Wool	100	0.36	59	0
11		120	0.301	61.8	0
12		140	0.267	64.4	0
13		160	0.239	67.1	0
14		180	0.22	69.8	0

Table 3.6: Characteristics of basement ceiling insulation materials.

N	Insulation types	Thickness (mm)	U-value (W/m^{2}K)	Cost (€/m^2)	GWP (kg CO_2-eq/m^2)
0	XPS	100	0.271	29.6	10.1
1		120	0.235	32.7	12.1
2		140	0.207	35.9	14.2
3		160	0.185	41.9	16.2
4	EPS	100	0.289	25.1	8.2
5		120	0.251	27.3	9.8
6		140	0.222	29.9	11.5
7		160	0.198	32.3	13.1
8	Sheep Wool	100	0.299	27.2	0
9		120	0.262	29.9	0
10		140	0.231	32.7	0
11		160	0.207	35.5	0
12		180	0.188	38.2	0

Table 3.7: Characteristics of windows.

N	Window types	U-value (W/m^{2}K)	Effective total solar energy transmittance (%)	Cost (€/m^2)	GWP (kg CO_2-eq/m^2)
0	Low e-glazing, air filled	1.9	62	350	37.8
1	Low e-glazing, argon filled	1.3	60	370	38.0
2	Low e-glazing, krypton filled	1.1	59	440	40.3
3	Highly insulating glazing	0.6	41	520	39.1

Table 3.8: Characteristics of building tightness improvements

N	Specification N_{50} (1/h)	Cost (€/m^2)
0	3	5
1	2	10
2	1	17
3	0.6 (passive house standard)	28

Table 3.9: Characteristics of heating systems.

N	Heating system types	EF (kg CO_2-eq/kWh)	η (%)	Cost (€/unit)
0	Condensing oil-fired boiler	0.319	90	9000
1	Condensing gas-fired boiler	0.258	90	11000
2	Gas-fired combined heat and power (CHP)	0.115	85	35000
3	Electric brine-water heat pump	0.641	300	25000
4	Low-temperature boiler for gas combustion	0.277	75	4000

For instance, if 'minimize annual operational energy consumption' is one of the objectives, the annual energy consumption indicator is chosen to measure the objective function, and the building energy simulation module in the building performance assessment model is thus chosen to calculate the indicator.

The building performance assessment model consists of several predefined and programmed modules to calculate the numerical indicators in terms of the competing design criteria. Once the optimization model runs, the optimizer will call the corresponding modules simultaneously and they will automatically return the objective values to the optimizer for the next optimization process. There are two types of relationships between different modules, Module 1 and Module 2 (Figure 3.10). If modules receive the inputs separately, they are connected in parallel in the optimizer. If Module 2 needs the causation results from Module 1, they are connected in series. In this case, if the design team select Module 2, Module 1 will also be involved. The configurations of the modules are manually completed by the design team.

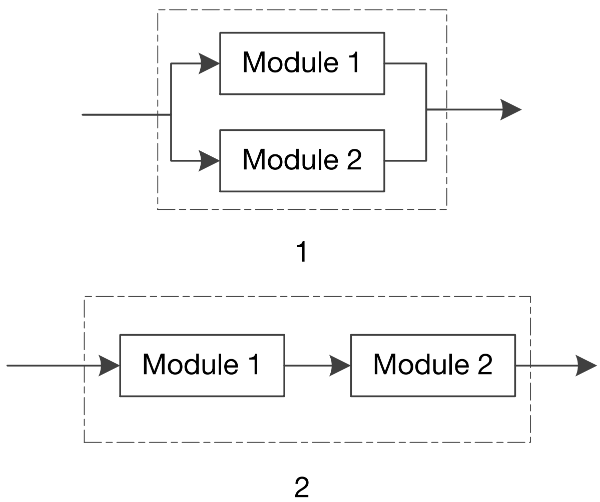


Figure 3.10: Module relationships in the building performance assessment model

As analyzed before, three objective functions are identified in the case study. The initial investment cost includes costs for the selected EEMs and the labor costs, and non-energy retrofit activities are not invloved. The initial investment cost is calculated by the following equation:

$$R_1 = \sum_{i=1}^{n} IC_i \tag{3.6}$$

where IC_i is the investment cost (€) for the ith selected EEM and its additional cost for labor, and n is the total number of the selected EEMs.

Building energy consumption can focus on an office building in Germany, the adopted approach is based on DIN V 18599, a holistic performance assessment method developed for German non-residential buildings. The building energy simulation/calculation module was implemented in VBA (Visual Basic for Applications) for Microsoft-Excel derived from the 'Excel tool for the DIN V 18599' by Fraunhofer Institute for Building Physics [93]. It was developed to calculate various energy performance indicators including annual operational energy consumption. In general, the annual operational energy consumption is expressed as:

$$\begin{aligned} R_2 = &\sum (Q_{h,f,i} + Q_{h,aux,i}) + \sum (Q_{w,f,i} + Q_{w,aux,i}) \\ &+ \sum (Q_{l,f,i} + Q_{l,aux,i}) + Q_{v,aux} + \sum (Q_{c,f,i} + Q_{c,aux,i}) \end{aligned} \tag{3.7}$$

where $Q_{h,f,i}$ ($Q_{h,aux,i}$) is the delivered (auxiliary) energy (kWh) supplied to the heating system by the energy carrier i and likewise, subscripts w, l, v, c signify domestic hot water system, lighting system, ventilation system and cooling system, respectively.

The annual GWP (CO_2-eq emissions) related to heating energy and the embodied GWP of EEMs are considered and compared with different solutions. A general equation for computing the annual GWP of a building is:

$$R_3 = \sum_{i=1}^{n} a_i GWP_i / L_i + Q_h \cdot EF/\eta \tag{3.8}$$

where a_i is the gross amount of EEMs (m^2 for the EEMs of façade improvements) used in the building and $GWP_i(x)$ is the global warming potential (kg CO_2-eq/m^2) of EEM i. L_i is the life time of EEM i; Q_h is the annual heating energy consumption (kWh/a); EF is the primary GWP factor (kg CO_2-eq/kWh) of the heating device used in the solution, and η is the corresponding heating system efficiency (%). In this equation, the embodied GWP of the existing building is not considered and the criterion value does not represent the actual annual GWP, but it can be used to compare different solutions.

The design constraints include envelope physical values, annual energy consumption and envelope air leakage set out by EnEV 2014. Indoor air quality and climatic conditions such as annual temperature and solar radiation are considered by defining the boundary conditions in the selected energy simulation module.

3.5.4 The simulation-optimization approach

After introducing the list of alternative EEMs and their properties into the optimization model, the concurrent optimization of the initial investment cost, the annual operational energy consumption and the annual emissions GWP is then carried out by means of the developed optimization model. In this study, 800 simulation runs are performed using a population size of 40 individuals and 20 generations. The whole structure of the optimization approach for the case study is shown in Figure 3.11.

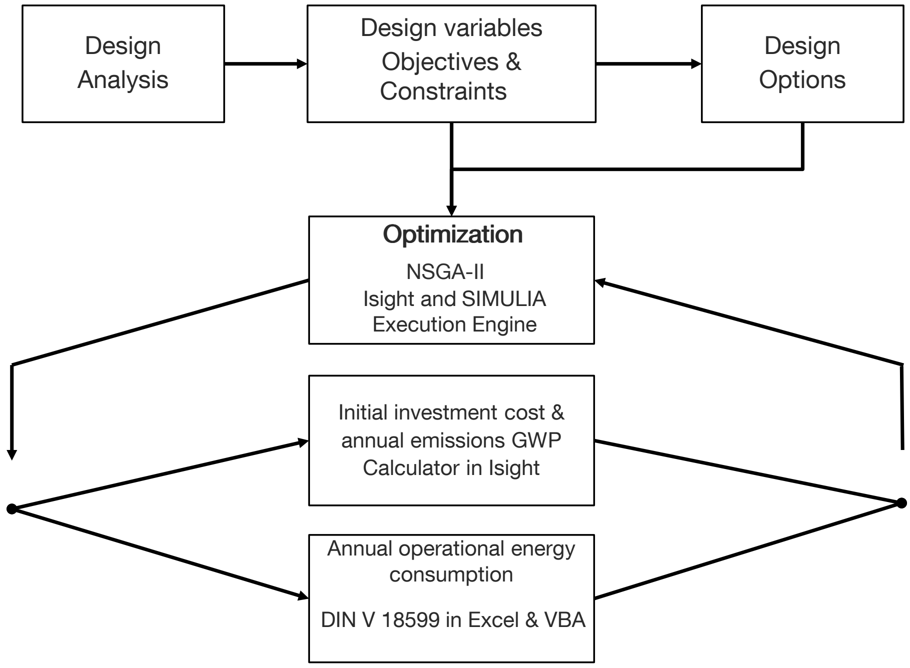


Figure 3.11: The structure of the optimization approach for the case study in Aachen, Germany. The design variables, criteria and constraints identified in the design analysis step are set as the inputs of the optimization process. The set of design options serves as the design space. The three objective functions are optimized simultaneously.

3.6 Evaluation of the optimization results

The objective functions constitute a three-dimensional space that contains a spatial distribution of the candidate solutions. In this study, 120 non-dominated Pareto optimal solutions are determined (Figure 3.12 on the facing page). Table A.1 on page 108 shows all the Pareto optimal solutions and the corresponding values in the three-dimensional criterion space, in which x_i represents the six design variables described in Section 3.2. Since each solution represents a unique assignment of weight factors of the three objectives, choosing different solutions from the Pareto frontier will lead to different trade-offs of energy, cost, and environment savings.

To aid interpretation of the Pareto optimal solution, the two-dimensional projections are shown in Figure 3.13 on the facing page. Each 2D projection shows the trade-off between two of the three objectives. The Pareto optimal solutions, marked with red dots, are not dominated by any other solutions. In order to verify the proposed methodology, a predefined solution by a local design team is compared (the green square in Figure 3.12 on the next page and Figure 3.13 on the facing page). The corresponding values for the three objective functions are: initial investment cost € 94,000, annual operational energy 55,700 kWh, and annual GWP 6,020 kg CO_2-eq. From Table A.1 on page 108 it can be noticed that multiple optimal

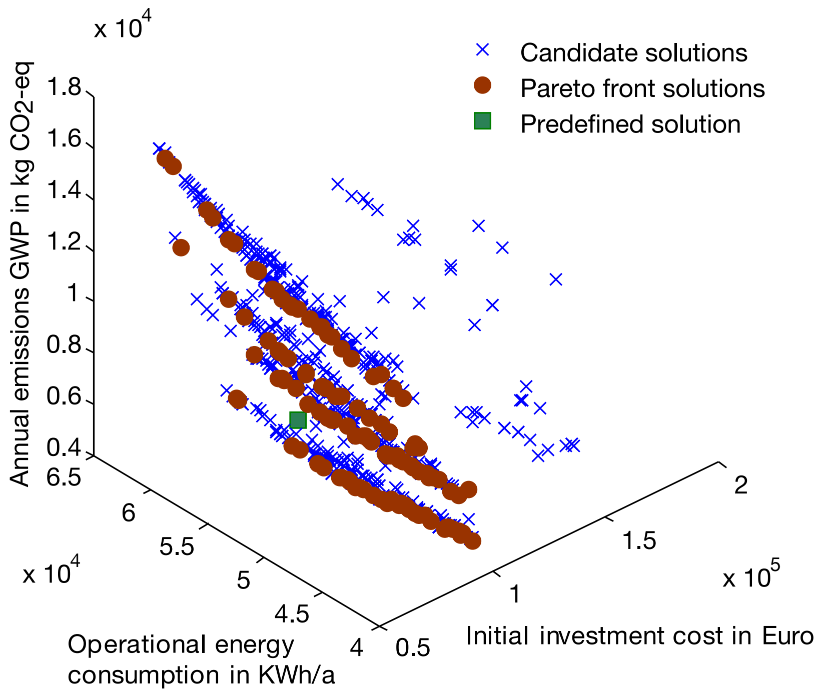


Figure 3.12: The Pareto optimal solutions and the candidate solutions of the case study

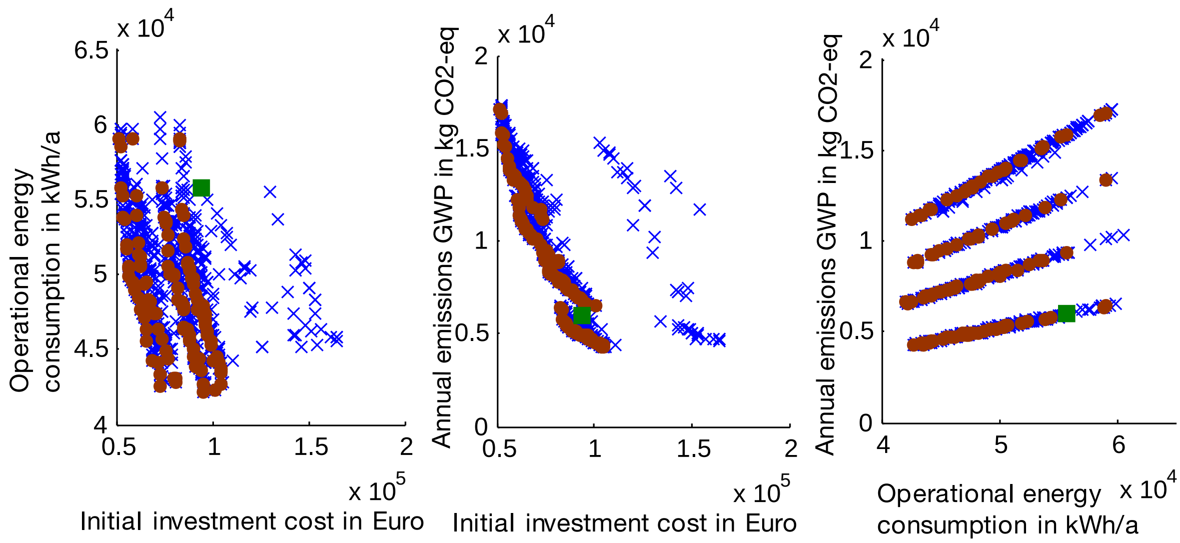


Figure 3.13: The two-dimensional projections of Pareto optimal solutions.

solutions (e.g., No. 5, No. 19, No. 33) perform better than the predefined solution regarding for all the criteria. For instance, compared with the predefined solution, the No. 5 scenario has 7.7%, 9.0%, and 10.4% improvements on initial investment cost, annual operational energy, and annual GWP, respectively.

In most cases, there are more than one, sometimes even hundreds of optimal solutions. However, the benefit of MOO can only be realized if these optimal solutions can be analyzed properly. In order to access the qualities of the optimal solutions, other techniques have to be applied. In this way, the single solution or a set of alternative solutions that satisfy the stakeholders' preferences are able to be identified for further detailed design. According to Brownlee and Wright [94], these techniques are categorized into two classes. The first is qualitative analysis based on observation of the solutions on the Pareto frontiers. There are approaches that apply 2D plots [95], rendered images [96], table-based comparisons [94, 97], identification of solution groups [37], pairs of objectives comparisons [98], etc. The second class of approaches includes quantitative metrics for comparison of the solutions on the Pareto frontiers [99, 100]. Mela et al. [101] studied the application of MCDM methods to compare the Pareto optimal solutions. It shows that the MCDM methods are very useful in finding the satisfying solution from the MOO-based Pareto solutions. In this study, an analysis model based on multiple-attribute value theory (MAVT), a particular kind of MCDM, is applied to this case study. MAVT allows one to simultaneously take into account indicators with different scales that refer to the three criteria. As a result, a holistic ranking based on the three above mentioned criteria and a list of normalized scores for each Pareto solution are presented in Table 3.10 on the facing page. A detailed solution analysis method based on MCDM is developed and will be explained in Chapter 5 on page 77.

For example, Rank 1 is the scenario of No. 76, which includes 180 mm EPS insulation on the external walls, 160 mm EPS insulation on the roof, 160 mm EPS insulation on the basement ceiling, high insulation glazing, improvement of the air tightness to N_{50}=1 1/h, and low-temperature boiler for gas combustion. The initial investment cost is € 73,200, the annual operational energy is 42,600 kWh, and the annual GWP is 11,200 kg CO_2-eq. Compared with Rank 2, which is No.107, these two scenarios differ in the types of insulations on the basement ceiling and the improvements of the air tightness. Figure 3.14 illustrates the comparison between the energy efficiency measures applied in the scenario of No.76, regarding energy savings, GWP emission savings, and initial investment costs. A model that describes the current state of the building has been preliminary defined as the baseline, so that the improvements of the proposed solution on different facets can be identified. Each selected EEM is then added to the baseline model in sequence, and the changes on the three performance indicators are measured. The ratios of annual operational energy saving and annual GWP emission savings are calculated based on the baseline model, while the ratio of initial investment cost is the ratio of each EEM cost to the total amount of initial investment cost. Due to the insulation of the external wall and sloped roof (i.e., x_1, x_2), a large part energy consumption can be saved. In addition, the costs are much lower than installing high insulation glazing (i.e.,

Table 3.10: Rank of the optimal solutions based on multi-attribute value theory (MAVT).

Rank	No.	Score	Rank	No.	Score	Rank	No.	Score	Rank	No.	Score
1	76	1.00	31	112	0.81	61	4	0.58	91	119	0.47
2	107	0.98	32	74	0.81	62	40	0.57	92	8	0.47
3	26	0.96	33	58	0.80	63	86	0.56	93	13	0.47
4	113	0.95	34	90	0.78	64	108	0.56	94	68	0.46
5	79	0.94	35	11	0.78	65	20	0.56	95	83	0.46
6	72	0.90	36	24	0.75	66	78	0.56	96	62	0.46
7	51	0.90	37	69	0.75	67	104	0.55	97	35	0.46
8	21	0.90	38	57	0.73	68	66	0.55	98	42	0.45
9	46	0.89	39	60	0.73	69	27	0.54	99	116	0.45
10	114	0.89	40	15	0.70	70	9	0.54	100	1	0.45
11	36	0.89	41	110	0.70	71	52	0.54	101	5	0.44
12	55	0.88	42	63	0.68	72	61	0.53	102	64	0.44
13	71	0.87	43	48	0.67	73	100	0.53	103	84	0.43
14	56	0.87	44	30	0.65	74	16	0.52	104	19	0.43
15	99	0.87	45	95	0.64	75	2	0.52	105	3	0.43
16	96	0.87	46	97	0.64	76	28	0.51	106	22	0.43
17	81	0.86	47	80	0.63	77	47	0.51	107	33	0.43
18	91	0.86	48	102	0.63	78	39	0.51	108	77	0.40
19	14	0.85	49	50	0.63	79	118	0.50	109	34	0.40
20	59	0.85	50	106	0.63	80	54	0.50	110	65	0.39
21	89	0.85	51	98	0.63	81	31	0.50	111	87	0.39
22	7	0.85	52	23	0.63	82	41	0.49	112	45	0.38
23	109	0.84	53	38	0.62	83	10	0.49	113	73	0.31
24	85	0.84	54	105	0.62	84	32	0.49	114	43	0.29
25	17	0.84	55	44	0.62	85	82	0.48	115	111	0.28
26	120	0.84	56	94	0.61	86	6	0.48	116	117	0.28
27	115	0.84	57	92	0.61	87	67	0.48	117	103	0.28
28	75	0.83	58	12	0.60	88	93	0.48	118	37	0.28
29	101	0.82	59	18	0.59	89	29	0.48	119	25	0.00
30	49	0.82	60	88	0.58	90	70	0.47	120	53	0.00

x_4). It is also found that with a relatively inexpensive low-temperature boiler for gas combustion, the emission saving of GWP is significant. The comparison shows the contributions of each EEM, but a holistic cost-effective reduction on energy use and GWP emission cannot be achieved without the combination of the various design variables. The interaction of the subsystems are important to deal with [102], and these interactions may cause different impacts on building performance when selecting different EEMs, requiring a complex combination of energy efficiency technologies. This is also why solutions with various design variables instead of individual EEM are investigated.

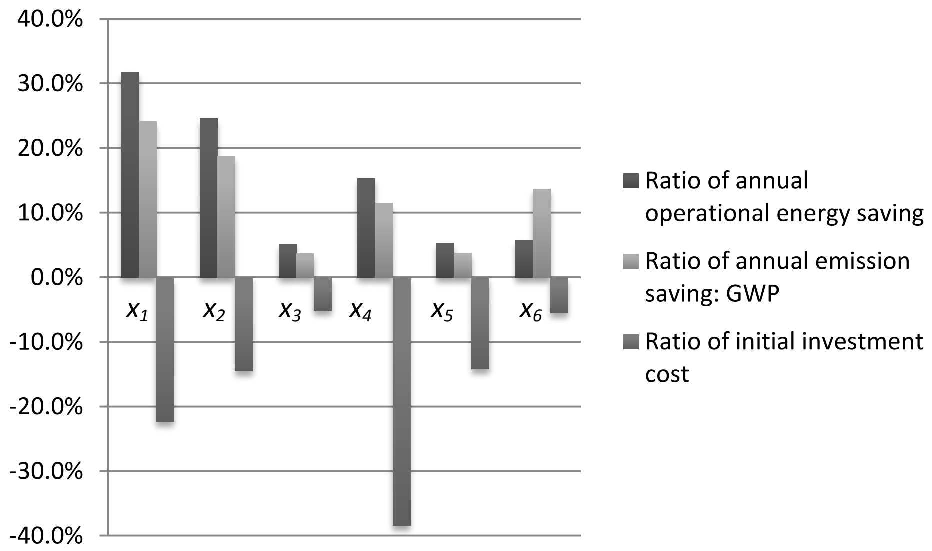


Figure 3.14: The ratios of the energy savings and GWP emission savings (the current state of the building as the baseline), as well as the initial investment costs. Comparison between the energy efficiency measures applied in the scenario of No.76. x_i represents the six design variables described in Section 3.5.2 on page 29.

3.7 Conclusion

Nowadays an extensive set of EEMs (energy efficiency measures) is available on the market and design teams have to compromise between stakeholders' diverse and often conflicting requirements in order to find a satisfactory solution. In contrast to the other approaches mentioned, this approach provides an integrated framework to identify the stakeholder requirements and potential energy efficiency measures, build and optimize the large design space, and determine the best solutions, in a holistic way. In addition, mathematical optimization and evaluation techniques are integrated into the whole process, which in the meantime considers the important role of stakeholders by carrying out the analysis procedure. By this means, building retrofits are explored in an integrative way so as to overcome the fragments of the planning process in the early phase.

The current study established a model to support decision-makers in making informed decisions on energy efficiency solutions in the early design phase. The new methodology connects the multiple and in most cases competing objectives with the large number of potential energy efficiency measures. The new methodology identifies the stakeholders' requirements and the potential EEMs by means of an adapted QFD procedure. In addition, the design space is established and effectively explored in a MOO procedure and a MCDM (multi-criteria decision-making) procedure in sequence. When exploring the design space, it is important to deal with the objective functions, design variables, and constraints according to the characteristics of the building — a task that inevitably is based on human judgment by the design team. To this end, a framework is applied that includes requirement analysis techniques to identify and quantify stakeholders' concerns and needs. In the optimization stages, the building performance assessment model consists of various modules to calculate the numerical indicators in terms of the selected design criteria. The methodology combines these approaches and is applied to buildings as a whole with all its design and retrofit aspects.

The developed methodology contains an analysis procedure to be carried out by design teams and a numerical procedure of optimization carried out by computer. The analysis procedure aims to set up the optimization model properly. The automatic optimization cycle considers conflicting objectives simultaneously without neglecting the design constraints set by the design team. The QFD-based tool allows the design team to set up the MOO model according to the characteristics of the building. The interactive cycle between the design team and the optimizer allows the evaluation of the optimal solutions and the optimization model improvement by taking human reasoning into the whole process.

The case study highlights the major advantage of the proposed framework, which is to provide a platform to integrate requirement analysis and optimization for a thorough exploration of the design space of retrofit solutions. A Pareto frontier is presented by the optimization cycle with a set of optimal solutions. Each optimal solution represents a certain combination of EEMs and a unique assignment of weight factors of the conflicting objectives. To access the qualities of the optimal solutions, MCDM techniques are then applied. A detailed MCDM model and its application will be explained in Chapter 5.

Chapter 4

Retrofitting office buildings in northern China

4.1 Introduction

The fast growing economy of China has led to a huge need for urban construction, causing significant energy demands and CO_2 emissions. The statistical data shows that the built-up area for offices has grown twelve times from 1978 to 2008 [103]. It is expected that the percentage of office buildings will increase due to China's continuing economic growth and urbanization [104]. Conversely, only 1% of the existing building stock is energy efficient in northern China, as building quality is sacrificed for quantity in undisciplined building development [105]. Therefore, a huge potential is emerging for office building retrofits, and the range of options for building energy retrofits is expanding. It is estimated that this market will be 1.5 trillion CNY (240 billion USD) covering 570 million square meters by 2020 [67].

During the past few years, several programs to retrofit the office building stock have been carried out, and many energy efficiency measures (EEMs) are currently readily available in China.By and large, the energy retrofitting of existing office buildings has not been fully investigated and, to date, its implementation has been insufficient. In addition, recent studies have shown that the selection and integration of EEMs in the different climatic regions of China were seldom considered [106–108]. For office building energy retrofits in China, the current study introduces a systematic approach for exploring a wide range of building and system integrated solutions. The methodology is designed to support the generation of optimal solutions for energy retrofitting of the existing office building stock in accordance with stakeholder objectives and constraints. A well-structured methodology developed in Chapter 3 on page 17 is deployed, and as the office building is very representative in northern China where both heating and cooling are required, a general conclusion is reached.

4.1.1 Office building energy consumption in China

Before analyzing office building energy retrofits, one question needs to be answered: how much energy do office buildings in China consume? However, there is no official system in China that systematically collects energy use information in the building sector. Literature reviews have found that there are only a few studies that investigated the heating and cooling of office buildings in China. Three recent studies give a picture of the current situation. He et al. [11] analyzed a large set of office buildings in China, and found that for ordinary office buildings the electricity consumption falls in the low range, between 33.6 and 77.5 kWh/m^2 per year (excluding district heating energy use). Peng et al. [109] analyzed more than 400 commercial buildings in southern China, and found that their annual electricity consumption ranged from 50 to 100 kWh/m^2 (including cooling). Based on a survey in 2006, Jiang [110] showed that large-scale public buildings (floor area of a single block building exceeding 20,000 m^2) account for 5%–6% of the total urban construction; however, these buildings consume 100–300 kWh/m^2 of electricity annually. Although each study emphasizes different aspects of this problem, studies also show that the energy consumption office buildings in China fall into a lower range compared with buildings in developed countries, both for per capita and per unit area calculations. On average, China's commercial buildings consumed 70 kWh/m^2 of final energy in 2005, far less than the 194 kWh/m^2 in Germany, 226 kWh/m^2 in Japan, and 356 kWh/m^2 in the United States [111, 112]. The gap becomes even greater when comparing per capita energy consumption. In 2005, the annual energy consumption per capita in China for commercial buildings was 580 kWh, far less than the 3,800 kWh in Germany, 8,000 kWh in Japan, and 17,000 kWh in the United States [113].

The relatively low energy consumption in China office building stock may give us an illusion that most of these buildings are energy efficient. However, many studies have proven that relatively low energy consumption is neither the result of high energy efficiency level, nor the awareness sustainable development. The low energy use is attributed largely to a different lifestyle, which is highly related to economic development [111]. The current standard of living in China is still relatively low, leading to a lower energy usage that sacrifices living comfort to reduce energy bills. Richerzhagen et al. [105] also found that Chinese people have little experience of high living standards and show almost no preference for energy efficient buildings due to their relatively short-term planning horizon.

4.1.2 Existing problems

Although the average energy consumption of China's office buildings is still low, energy loss is quite high due to poor building insulation performance, poor heating systems, and inefficient heat distribution.

An elementary comparison of building-envelope insulation performance reveals the current situation for existing office buildings. The first energy efficiency design standard for public buildings, the China national standard GB50189-2005 [114], was issued on July 1, 2005 and has not been updated since. The standard defines specific requirements for five climate zones: severe cold region, cold region, hot-summer cold-winter region, hot-summer warm-winter region, and temperate (mild) region (Figure 4.1). The cold zone of China has similar climate conditions to Germany and climate zone 4 of the United States. To discover the gaps between China's energy efficiency code and the those of other countries, a comparison is of great interest. The current energy efficiency regulation (EnEV 2014) in Germany came into force in 2009 [115]. EnEV 2014 defines the minimum standard of thermal insulation for building envelopes. In the U.S., the comparable energy code is ASHRAE 90.1 2010 [116], which defines a climate classification system with eight climate zones. Table 4.1 on the following page compares the building-envelope requirements for office buildings for these three standards. It is quite clear that the Chinese standard has much higher minimum U-factors for all building envelope components, especially when compared to EnEV 2014. In addition, enforcement of the standard remains a problem even though the standard is mandatory. According to Hong [117], lack of effective support and political will for its enforcement lead to the ineffective enforcement. In fact, 95% of existing buildings in China have poor insulation performance and do not meet the current standard [118].

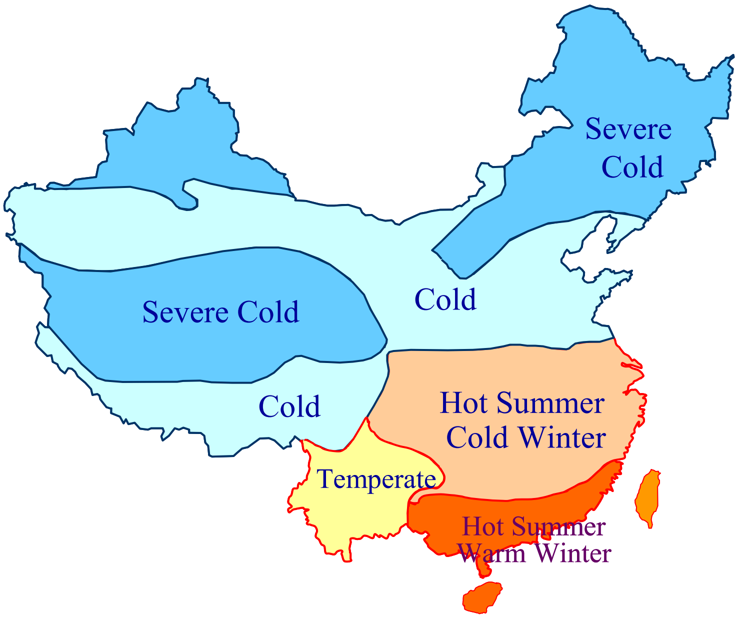


Figure 4.1: China's climate zones according to the average temperature in the different regions

As for thermal comfort, district heating systems are installed for most buildings in northern China using inefficient practices. The Chinese district heating systems are roughly 20%-30% less efficient than the separate, independent heating systems that are predominant in Germany [119]. Heating and cooling in the cold region of China tend to be inefficient due to poor thermal insulation performance. Additional major losses are caused by heating imbalances and the lack of heat control. Further, according to continuous surveys from Tsinghua University [67], the control, management, and maintenance of heating, cooling, and air conditioning

Table 4.1: Basic requirements for office building envelopes in the cold zone of China, Germany, and climate zone 4 of the U.S. (U-value in W/m^{2}K)

Building-envelope component	GB50189-2005 China (Cold zone)	EnEV 2014 Germany	ASHRAE 90.1 2010 United States (Climate zone 4)
Outside walls	0.60 0.50	0.24	0.36-0.59
Outside windows, French doors	2.0-3.5	1.3	2.27-3.12
Ceiling, roofs and roof pitch / Flat roofs	0.55 / 0.45	0.24 / 0.20	0.15-0.31
Ceilings and walls against unheated spaces or the earth	1.5	0.3	*F 1.26 * F factor, perimeter heat loss factor for slab-on-grade floors, in W/mk
Floor construction	1.5	0.5	0.49

(HVAC) systems are fairly poor in China's office buildings, leading to a substantial waste of energy.

4.2 Analysis of building energy use scenarios

Retrofitting existing buildings is considered an effective way to reduce energy consumption and carbon emissions during the operational periods of building use. An energy retrofit strategy should be established to meet the building's future energy use. China is at an important transformative stage, so it is important to understand the differences between current and future energy use patterns. A map of ratio of energy pricing per capita income for China, Germany, and the U.S. is shown in Figure 4.2 on the next page [120–123]. It shows that the ratios for the U.S. and Germany remained very low and stable, while the ratio for China is decreasing continuously. Recently, China's National Development and Reform Commission (NDRC) claimed that "China's per capita GDP has reached more than 6700 USD, and now belongs to the ranks of upper middle income countries based on the standards released by the World Bank" [124]. Higher income tends to lead to a higher living standard, so the pattern of building energy use in China is likely to follow the path of developed countries. In addition, the Chinese government is committed to achieving "energy-saving and emission-reduction" to address the increasingly problematic situation in domestic energy use [125].

One of the main challenges in the energy retrofit design of existing buildings in China is to ensure that indoor environment will improve, which is likely to consume more energy [126]. Conversely, building energy demand should not follow the path of high consumption and remain at a relatively low level instead.

4.2.1 Lessons from Germany

Contrary to common thinking, higher income doesn't have to lead to increased energy consumption. Germany as an example has made energy efficiency a top priority, and is very representative of continuous decreasing building energy use. As is illustrated in Figure 4.3 on

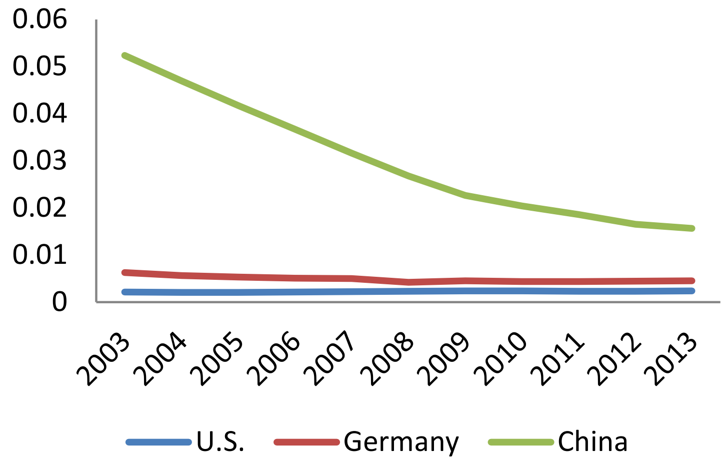


Figure 4.2: Price of one megawatt hour of electricity as a fraction of per capita income (the vertical axis represents the ratios).

the following page, Germany's energy performance requirements have reduced over 70% of primary energy demand for heating during the past 30 years.

It is found that technical feasibility of reducing energy use is investigated and proved by frontier research first. Later on the economic feasibility of these technologies is adopted by the market. The requirements were established 10 to 20 years after the demonstration projects. It is targeted to reduce the primary energy requirement by 20% from 2008 level by 2020, and by 80% by 2050 in Germany [8]. As the replacement rate of existing buildings by the new-built remains very low in Germany, retrofitting the existing buildings is very important for the target. The energy retrofits have to be 'deep' so as to achieve the challenging goal, and each energy retrofit is demanded to follow the current energy standard. Therefore, effectively implementing EEMs in China's sizeable building stock will most likely play a central role in mitigating the conflicts between the increasing living standard and the practical needs for energy efficiency.

4.2.2 Analyzing the energy-use pattern of China's office buildings

The pattern of energy use has much to do with thermal comfort, lighting, hot water use, and indoor air quality. For office buildings, the German standard DIN V 18599 [128], defines the guideline conditions for German non-residential buildings. Compared to the current energy-use pattern of China's ordinary office buildings, the German standard gives a stricter guideline over the indoor thermal comfort and lighting conditions. It is assumed that the use-pattern of China's office buildings will be close to the German standard, with increasing needs for better working environments and thermal comfort. Tables 4.2 and 4.3 on page 47 and on page 48 define the boundary values of use for typical rooms in non-residential buildings; these can also be used as guidelines for future use-patterns of office buildings in northern China.

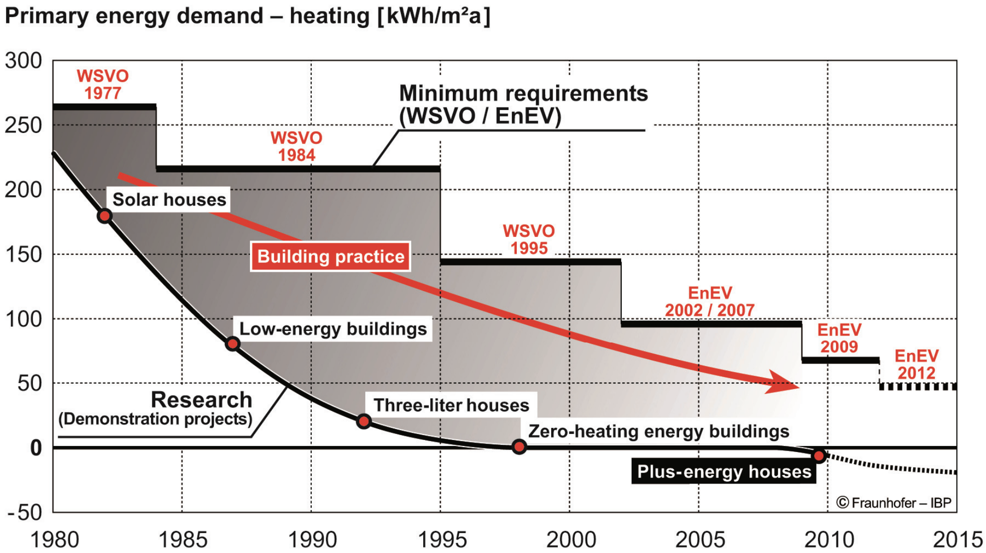


Figure 4.3: Development of energy-saving construction in Germany, reprint from [127]

Table 4.2: Guideline values for the boundary conditions of use for non-residential buildings – DIN V 18599, compiled from [128]

Type of usage			Personal office (single occupant)	Workgroup office (two to six workplaces)	Landscaped office (seven or more workplaces)	Meeting, conference and seminar room	Toilets and sanitary facilities	Auxiliary spaces (without habitable rooms)
Usage and operating times	Beginning of usage	Time	7:00	7:00	7:00	7:00	7:00	7:00
	End of usage	Time	18:00	18:00	18:00	18:00	18:00	18:00
	Daily usage time	h/d	11	11	11	11	11	11
	Annual usage days	d/a	250	250	250	250	250	250
	Daytime usage hours per annum	h/a	2543	2543	2543	2543	2543	2543
	Night-time usage hours per annum	h/a	207	207	207	207	207	207
	Daily operating hours of HVAC and cooling system	h/d	13	13	13	13	13	13
	Annual operating days of HVAC, cooling and heating systems	d/a	250	250	250	250	250	250
	Daily heating system operating hours	h/d	13	13	13	13	13	13
Lighting	Maintained illuminance	lx	500	500	500	500	200	100
	Height of the work plane	m	0.8	0.8	0.8	0.8	0.8	0,8
	Reduction factor for visual task area		0.84	0.84	0.93	0.93	1	1
	Relative absence		0.3	0.3	0	0.5	0.9	0,9
	Space/room index		0.9	1.25	2.5	1.25	0.8	1,5
	Reduction factor for lighting related to the building operating time		0,7	0,7	1	1	1	1
Indoor environment	Humidity requirements		w. t.	w. t.	w. t.	w. t.	–	–
	Minimum outdoor supply-air volume flow rate	$m^3/(h\cdot m^2)$	4	4	6	15	15	0,15
Heat sources	Persons	$Wh/(m^2\cdot d)$	30	30	42	96	0	0
	Equipment, machinery, appliances	$Wh/(m^2\cdot d)$	42	42	60	8	0	0

Table 4.3: Guideline values for common boundary conditions which apply to all types of usage, compiled from [128]

Internal set-point temperature for heating operation	21 °C [a]
Temperature reduction for set-back operation	4 K
Internal set-point temperature for cooling operation	24 °C
Minimum temperature, heating, design rating	20 °C
Maximum temperature, cooling, design rating	26 °C

[a] If the internal set-point temperature for heating for a particular type of usage (e.g. workshop or storeroom) is below 19 °C. (usage at low indoor temperatures), a value of 17 °C shall be assumed for both the internal set-point temperature for heating operation and the minimum temperature, heating, design rating.

DIN V 18599 defines a holistic performance assessment method for German non-residential buildings in energy consumption. According to EU Energy Performance of Buildings Directive (EPBD), "*energy performance of a building means the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes energy used for heating, cooling, ventilation, hot water and lighting*" [129]. The present study also adopts DIN V 18599 as the energy performance assessment method, so that the calculation theory is well integrated into the design. In order for DIN V 18599 to be adapted to the cold zone of China, some changes are required. From the methodology, aspects important to energy performance calculations are as follows: (i) weather data (e.g., temperature, solar irradiance); (ii) the mean daily heat flow through the ground [130]; (iii) primary energy factors; (iv) solar energy gain for the sanitary hot water generator; and (v) movable shading devices and effective total energy transmittance. The original values of the mean daily heat flow through the ground do not apply to northern China; therefore, an alternative approach was applied according to Li [131].

4.3 On-site investigation of the case study

The building for this research project was located in Shijiazhuang, the capital of Hebei province in the cold zone of China. The building is 22 m high and covers an area of 775 m^2, with a total construction area of 4068 m^2. The first phase of the building, a five-story brick-cement structure with 370 mm clay bricks, which have been outlawed in most cities since the late twentieth century, was completed in 1987. The second phase, a six-story frame structure with 250 mm aerated concrete external walls, was completed in 1993. The building is owned by a local building design and construction company, and has been used as an office building since construction. Figure 4.4 on the next page shows its exterior appearance, and Figure 4.5 on the facing page shows the architectural plan for a standard floor. This building is representative of typical office buildings built 20-30 years ago and that now require energy retrofits. It is estimated that in China this type of office building accounts for more than 95% of office buildings, and more than 70% of the total floor area of office buildings [132].

Figure 4.4: Appearance of the case study building in Shijiazhuang, China

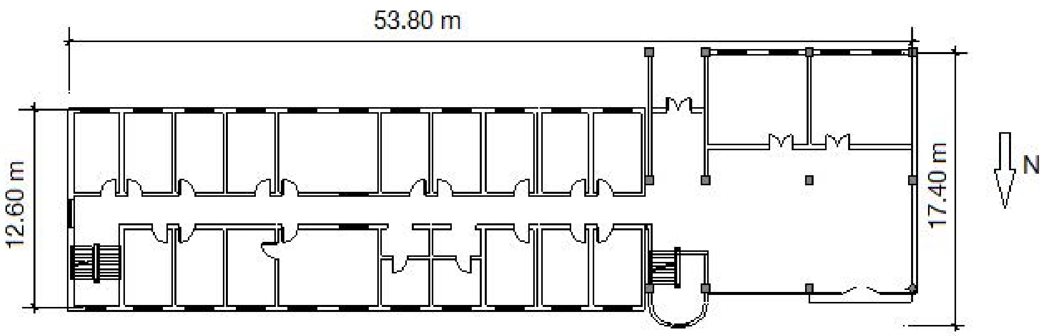


Figure 4.5: Architectural plan for a standard floor of the subject building

To understand the current energy status of the building, a preliminary investigation of the envelope, HVAC system, and lighting system was conducted (Table 4.4 on the next page). It is clear that the roof, exterior walls of Phase 1, and windows have poor thermal performance and fail to meet the current energy code.

Table 4.4: Thermal properties of the subject building envelope

Building component	Structure	U value (W/m^{2}K)	Heat transfer area (m^2)
Roof	8 mm SBS waterproof layer 20 mm cement mortar leveling blanket 100 mm aerated concrete insulation 70 mm cement mortar sloping layer 120 mm structural support layer	1.56	790
Exterior wall	granitic plaster layer 20 mm cement mortar leveling blanket 370 mm clay brick layer (250 mm aerated concrete layer) 30 mm cement mortar layer (including whitewashing layer or tile layer)	3.55 (Phase 1) 0.44 (Phase 2)	South 729.8, North 649.2, East 222.3, West 308.6 Total:1909.9
Deformation joint of the interior wall	20 mm cement mortar leveling blanket 240 mm clay brick layer	3.85	756
Exterior Window	Aluminum alloy single-glass sliding window	6.67	South 321.3, North 392.4, East 13.5, West 27.4 Total:754.6
Floor	30 mm cement mortar layer (including tile) 100 mm concrete 20 mm lime mortar plastering	2.83	60
Ground	30 mm cement mortar layer (including tile) 100 mm concrete	0.52 0.3	Peripheral:249.2 Non-peripheral:525.8 Total:775

The city's district heating system network (DHS) supplies the heat in the heating season. In a DHS, coal is used in combined heat and power (CHP) or boilers to heat the water for buildings to meet the heating demand in winter. Each city has a fixed heating period (e.g., the DHS in Shijiazhuang works from November 15th to March 15th of the following year, i.e., four months). The greatest disadvantage of the current heating system in this building is that, in winter, the offices on the north side are much colder than offices on the south side. Since no thermostatic valve is installed, heat is wasted in meeting rooms, storerooms, and other unused offices. The old split-type air conditioners are no longer efficient. The pipe insulation has deteriorated in places. Even worse is that the air conditioners have to run at a low temperature setting for long periods each year so as to offset the heat from the poorly insulated envelope. As for the existing lighting system, the T8 fluorescent lamps and the common ballast in the offices are not energy efficient and fail to meet the current national energy efficiency standards.

Other than on an international level, in China building heat loss index (W/m^2) is usually taken as the indicator to measure the heating energy demand in the heating period. Heat loss index means the heating power for 1 m^2 of floor area to keep the required indoor temperature, whilst the average temperature in the heating season is taken as the outdoor temperature. The heat loss of the building in a typical heating day is assessed based on the Design Standard for Energy Efficiency of Public Buildings GB 50189-2005 (see Table 4.5). The temperatures in offices, meeting rooms and corridors are defined to be 20 °C, 18 °C and 16 °C, respectively. The average outdoor temperature is assumed to be -0.6 °C during a 117-day heating period. The results show that the roof, exterior walls, windows, and air infiltration contribute to most of the heat loss in winter. These areas need significant attention in the retrofit design.

Table 4.5: Heat loss (transmission and ventilation) from the case study building's different components calculated based on GB 50189-2005. The weather conditions of Shijiazhuang are shown in Figure D.1 on page 119.

Source of energy losses	Average power of the heat loss in kW	Percentage of total heat loss (%)
Roof	17.8	11.9
Exterior wall	52.1	34.9
Deformation joint of the interior wall	2.7	1.8
Window	39.8	26.7
Ground	4.6	3.1
Floor	2.8	1.9
Air infiltration heat loss	29.4	19.7
The total heat consumption	149.4	100

Energy consumption of the DHS is calculated according to China's energy design standard. Total amounts of heating energy and coal consumption are calculated as follows:

$$Q_h = 24 \times Z \times q_H \times A \tag{4.1}$$

$$Q_{coal} = \frac{Q_h}{H_C \times \eta_1 \times \eta_2} \tag{4.2}$$

where Q_H represents the annual heating energy; Q_{coal} represents the total coal consumption for heating; q_H represents the index of heat loss (IHL) of the building (in W/m^2); A represents the building area (m^2); Z represents the heating period (days), which in Shijiazhuang is 117 days; H_C is the heat value of standard coal combustion (8.14$\times$10^3 Wh/kg); η_1 represents the heat delivery efficiency for the networks; and η_1 represents the energy efficiency of the energy systems.

In this case study, the heating consumption is around 120 kWh/m^{2}a. The calculated annual total amount of coal consumption for 1 m^2 heating space is 24.4 kg. A yearly electricity consumption of 2.8$\times$10^5 kWh (68.8 kWh for 1 m^2 using space) in 2013 is recorded. Unfortunately, there are no subentry metering devices in the building, so it is impossible to determine the subentry electricity consumption for each building component.

4.4 Application of the developed methodology

As a component of the research on systematic approaches to energy retrofitting strategies for office buildings, this study employs the previously defined methodology shown in Figure 3.1 on page 19 [72]. The methodology developed contains an analysis procedure to be performed by the design team and a numerical procedure for optimization by computer. The overall work flow is recorded in Figure 4.6 on the facing page. It begins with a workshop to collect information on the case study and to allocate the design team. A second workshop with an analysis procedure is then conducted. The analysis procedure aims to identify stakeholder requirements and the potential energy efficiency measures (EEMs). First, a pairwise comparison matrix is employed to obtain the weights of each criterion. A quality function deployment (QFD)-based model is then used to select potential EEMs for the subsequent optimization procedure. The automatic optimization procedure, which employs a multi-objective optimization (MOO) model, considers conflicting objectives simultaneously, without neglecting the design constraints set by the design team. The result, based on the methodology, is a set of optimal solutions that meet the stakeholders' requirements. Future analysis of these solutions can be made by multi-criteria decision making (MCDM) methods. In this manner, the single solution, or set of alternative solutions, which satisfies the stakeholders' preferences are identified for further detailed design. The interfaces of the tools that the design team apply are also shown in Figure 4.6 on the next page.

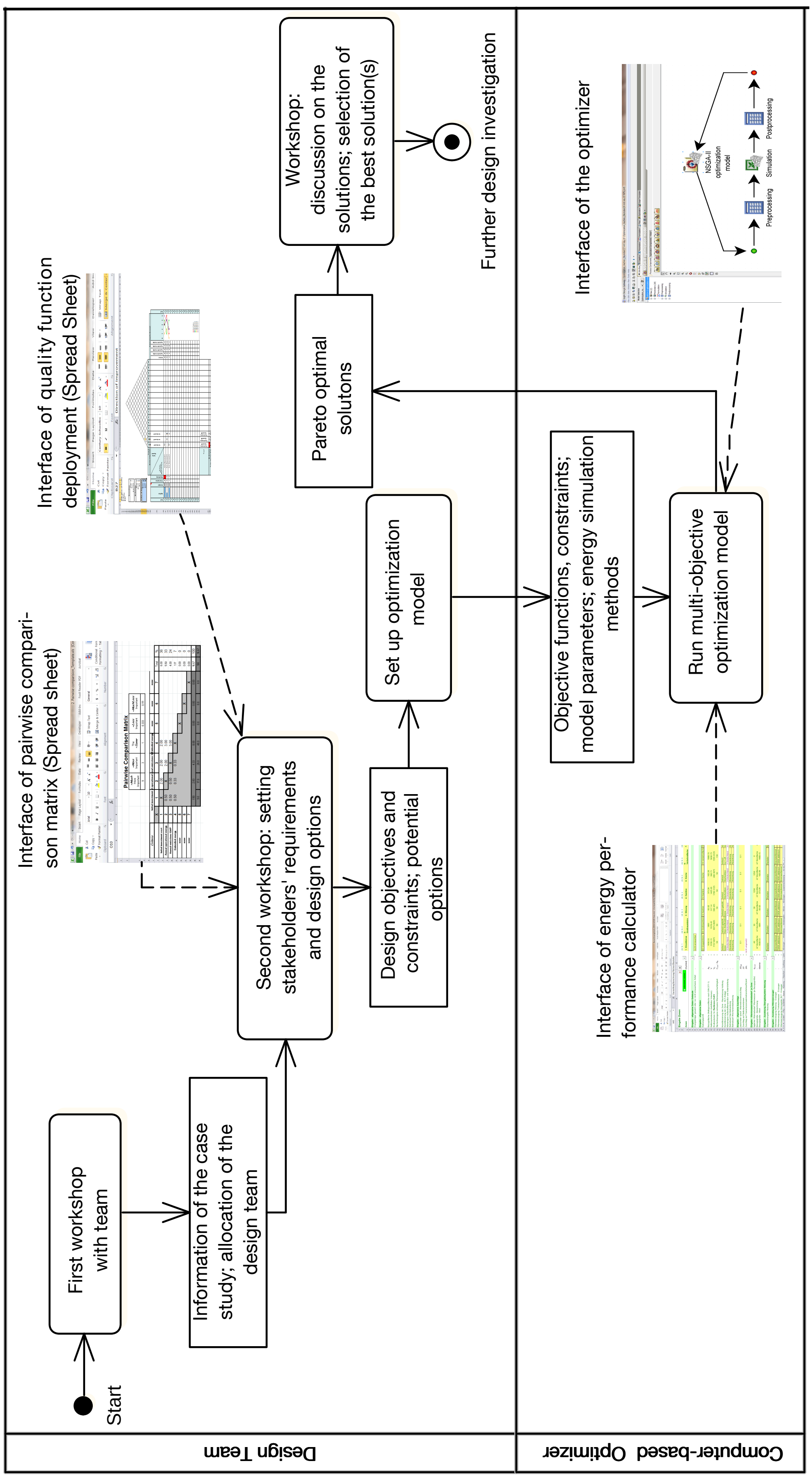


Figure 4.6: The activity diagram records the overall work process of the case study, based on Figure 3.1 on page 19. Each activity (e.g, a workshop) has an output for the next activity. The interfaces of the tools that the design team apply are also illustrated, and each of the interfaces can be found in Appendix B on page 109

4.5 Setting stakeholders' requirements and design options

When retrofitting office buildings, it is obvious that one of the main requirements is to make office buildings more energy efficient. Yet energy efficiency is only one of the many requirements that should be considered. Other requirements, such as low carbon emissions and low investment costs, may also need to be considered. The requirements and conditions of buildings differ from one another, so it is necessary to identify the stakeholders' requirements before formulating retrofit solutions.

A design team comprising two architects, two civil engineers, and two mechanical engineers from the company that owns the case study building was set up to work on retrofit solutions. After the on-site investigation and several meetings, a half-day brainstorming session to identify the stakeholders' requirements and design options was undertaken by the design team, a senior director, and the author.

The subject building is classified as an owner-occupied facility. This case study represents non-typical stakeholder interactions in that the participants are not only the occupants and the owners, but also the designers. However, despite organizational differences in the stakeholders' multiple identities, they have a substantially vested interest in retrofitting the office building to be energy efficient and environmentally friendly. In addition, they have sufficient expertise in building retrofits, which tends to generate more reliable results from QFD analysis.

The session has five main procedures.

1) Data collection

QFD is a model and a guideline for the process towards the design solutions. Thus, from the beginning, all the important stakeholders and their requirements for the specific retrofit project are identified and collected. The possible retrofit areas and EEMs under these areas that correspond to the project requirements and are applicable to the existing building are listed.

Data collection on stakeholder requirements began with a public discussion followed by selection of all relevant criteria and potential constraints from a list of stakeholder requirements by each participant. A full list comprising all selected requirements from each participant is shown in Table 4.6 on the facing page, while the constraints are derived from the project conditions.

2) Assessment

The collected requirements must be arranged and categorized, overlapping requirements are deleted and requirements of the same property are merged. These criteria are weighted based on their importance to the stakeholders. The listed retrofit areas and specific EEMs are evaluated according to their contribution to the fulfillment of each requirement. After collecting and analyzing data from stakeholders, a pairwise comparison matrix was applied during the workshop to formulate the list and determine the critical items that should be included (Table 4.7 on the next page). The participants discussed various requirements and, ultimately, ten requirements were listed for the pairwise comparison matrix. The design team then com-

Table 4.6: List of the requirements for the case study building

Criterion	Initial investment cost
	Net present value of the retrofit and energy investment
	Life cycle cost
	Annual operation cost
	Payback period
	Annual operational energy
	Annual electricity consumption
	Annual heating energy consumption
	Transportation and construction CO_2 emissions
	Annual CO_2 emissions
Constraint	Energy-saving standard
	Indoor air quality & thermal comfort
	Sanitary hot water
	Illumination

pared all the requirements, and the relative importance of each accords with the instructions in Section 3.4.1 on page 22. The matrix then defined the criteria and their weights.

Table 4.7: Pairwise comparison matrix to identify the relative importance of stakeholder requirements.

	CRITERIA WEIGHT	1	2	3	4	5	6	7	8	9	10	TOTAL	DECIMAL VALUE
1	Initial investment cost	X	0.33	1.00	3.00	3.00	3.00	3.00	3.00	0.33	0.33	16.99	0.12
2	Net present value	3.00	X	3.00	3.00	3.00	3.00	9.00	3.00	1.00	1.00	29.00	0.21
3	Life cycle cost	1.00	0.33	X	1.00	1.00	1.00	1.00	3.00	3.00	3.00	14.33	0.10
4	Annual operation cost	0.33	0.33	1.00	X	1.00	1.00	1.00	1.00	0.33	0.33	6.33	0.05
5	Payback period	0.33	0.33	1.00	1.00	X	1.00	3.00	1.00	3.00	3.00	13.67	0.10
6	Annual operational energy	0.33	0.33	1.00	1.00	1.00	X	3.00	3.00	0.33	0.33	10.33	0.07
7	Annual electricity consumption	0.33	0.11	1.00	1.00	0.33	0.33	X	0.33	0.33	0.33	4.11	0.03
8	Annual heating consumption	0.33	0.33	0.33	1.00	1.00	0.33	3.00	X	0.33	0.33	7.00	0.05
9	Transportation & construction CO_2 emissions	3.03	1.00	0.33	3.03	0.33	3.03	3.00	3.00	X	0.33	17.10	0.12
10	Annual CO_2 emissions	3.03	1.00	0.33	3.03	0.33	3.03	3.00	3.00	3.00	X	19.77	0.14
	COLUMN TOTALS	11.73	4.11	9.00	17.06	11.00	15.73	29.01	20.34	11.66	8.99	138.62	1.00

In the second workshop after the onsite investigation, a general description of energy flow in China's office buildings and its relation to energy retrofits is demonstrated to help the design team identify the improvements and determine any potential improvements in various building components (Figure 4.7 on the next page). Commonly used energy carriers and the functionalities of energy use in northern China are illustrated. The decision making level and its connection to building components is also shown in the figure. The design decisions determine how the building will be retrofitted; therefore, the figure also visually presents to the design team the impacts of decision-making on energy retrofits.

In this meeting, the participants proposed sixteen options for energy efficiency retrofits by identifying energy flow in the office building and its relation to energy retrofits (see Figure 4.7

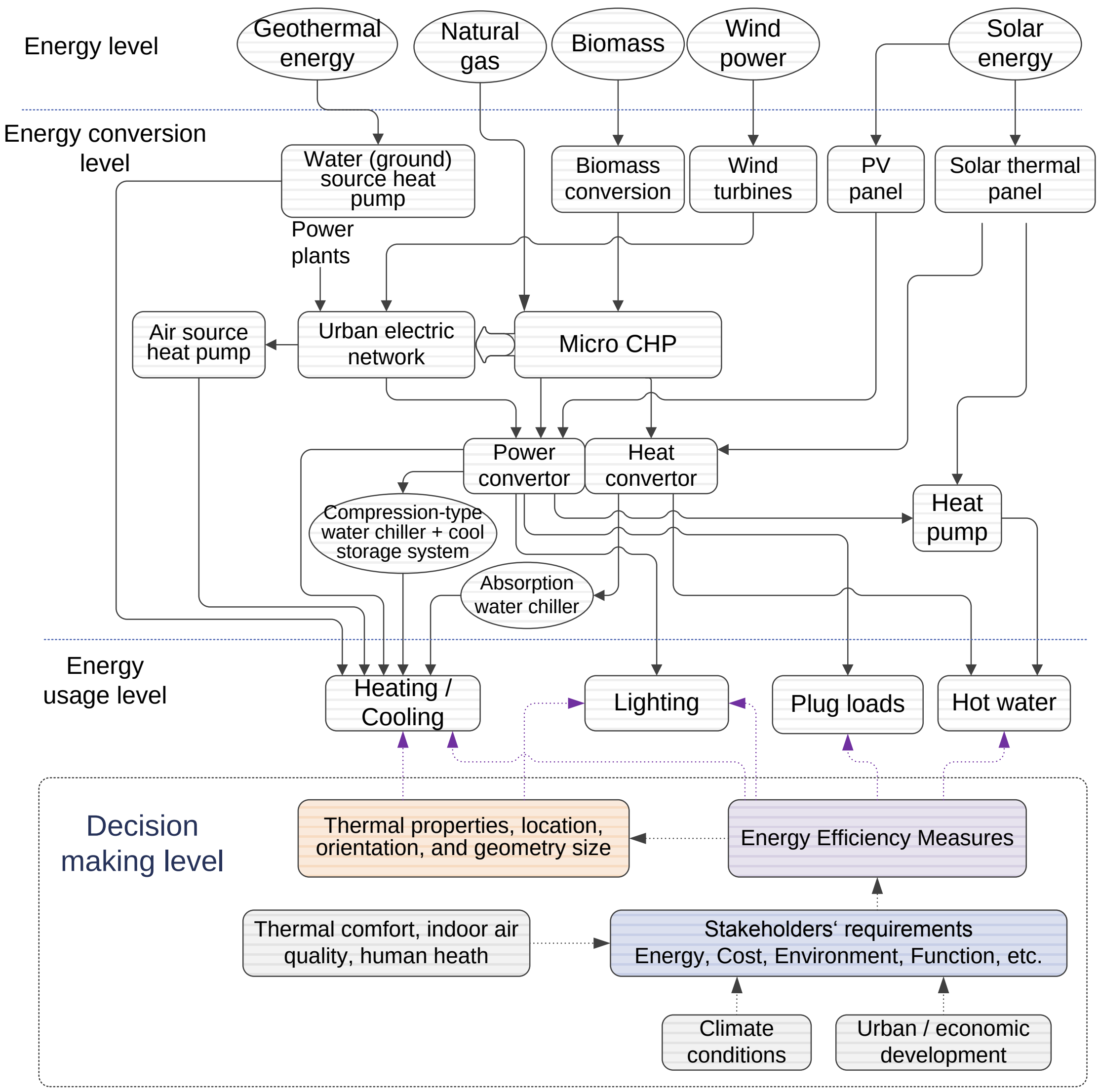


Figure 4.7: Energy flow in office buildings and its relation to energy retrofits. The energy systems in the energy conversion level will convert different energy resources for the energy usage level. The decision making level illustrates the interrelations between the stakeholders, the EEMs and the building characteristics. The decision making level is also highly related to the energy usage activities, which will in turn affect the energy systems and the energy sources

on page 56). These options include improvements to the building envelopes, HVAC systems, lighting system, and the utilization of renewable energy. It is worth mentioning that the selection of potential EEMs depends not only on the project conditions but also on the designers' expertise; therefore, other best EEMs might be absent. Table 4.8 lists the sixteen EEMs. The option of sustainable insulation materials is included to explore the possibility of sustainable retrofits. Building materials and products manufactured locally will be considered first for lower embedded transportation impacts; the use of products made from recycled, low emission materials is also preferable. The option of building energy monitoring system (BEMS) is considered because China's Ministry of Housing and Urban-Rual Development (MOHURD) advocates the use of BEMS for office buildings to systematically gather nation wide data for building energy use [133]. The basic idea of establishing the national system is to explore the potential for reducing building energy demand and improving indoor comfort by monitoring building services and energy use. In addition, BEMSs provides the base for the buildings' future energy updates.

Table 4.8: Selected sixteen potential energy efficiency measures for the case study

Energy efficiency measures	Energy efficiency measures
01 External wall insulation	09 Roof insulation
02 Ground floor insulation	10 Glazing insulation with sun shading
03 Sustainable insulation materials	11 Building air-tightness improvement
04 Improvement of the current district heating system	12 Distributed energy system (e.g. heat pumps)
05 New split-type air conditioner	13 Radiant cooling ceiling
06 Updates of lighting system	14 Photovoltaic (PV) system
07 Solar thermal panel	15 Wind turbines
08 Electric water heater	16 Building energy monitoring system (BEMS)

The workshop on selecting the potential design options also helped to identify two facts:

–Improvement of the current district heating system (DHS) is the best option to apply if the DHS is retained for the building. By installing thermostat on the heat inlet of the building's outdoor heating pipe network, the heat losses caused by the pipe system's hydraulic imbalance will be effectively reduced.

–The problem of rooms on the north side being much colder than those on the south side in winter can be mitigated once the building is well insulated and the heat distribution is well balanced. The design team proposed replacing the existing pipelines and radiators. The pipe system is to be changed to a vertical return single pipe network for the north and south sides independently. All existing radiators in the building are to be replaced with steel flat tube radiators. Thermostats are to be installed in each room for individual temperature control. The set of improvements introduced here is taken as the first step for any of the options for heating system retrofits.

3) Analysis method

In this step QFD (quality function deployment) matrices are established to display the technical correlation among retrofit measures, and attribute each measure a technical importance within the project. The participants were divided into four groups: the author (Group 1); the director (Group 2); two set of an architect, a construction engineer, and a mechanical engineer (Group 3 and Group 4). During the brainstorming session, each group established a QFD matrix in a spread sheet. Table 4.9 shows the completed QFD matrix by Group 1. The QFD matrices completed by different groups are attached in Appendix C on page 113. Each EEM was evaluated after the fulfillment of each criterion and constraint. The output of the QFD matrix is a list of weight factors for each EEM.

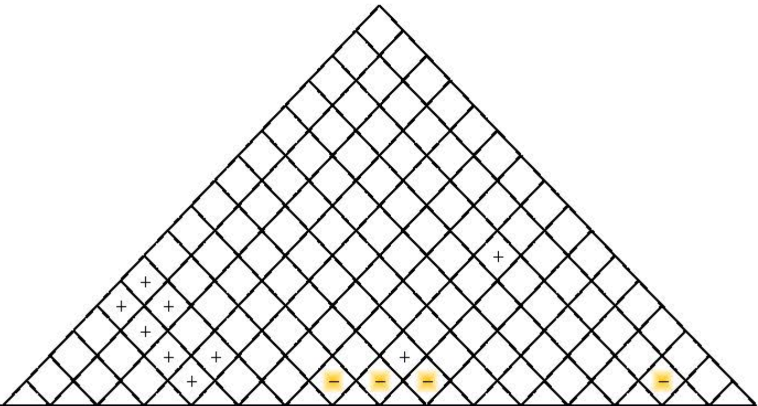
Table 4.9: Quality function deployment (QFD) matrix completed by Group 1

QFD: House of Quality

Project: Shijiazhuang office building
Revision: SHAO Yunming
Date: Feb 24th, 2014

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships		
Strong	9	●
Moderate	3	○
Weak	1	▽



Row #	Weight Chart	Relative Weight	Stakeholder Importance	Stakeholder Requirements / Energy Efficiency Measures	1 Insulate exterior walls	2 Insulate roof	3 Insulate ground floor	4 Insulation glazing with sun shading	5 Sustainable insulation materials	6 Improve building tightness	7 Improve the current district heating system (DHS)	8 Distributed energy system (e.g. Heat pump, CHP)	9 New split-type air conditioner	10 Radiant cooling ceiling	11 Update lighting system	12 Building Integrated Photovoltaic (PV)	13 Wind turbines on the roof	14 Solar water heater	15 Electrical water heater	16 Building energy management system (BEMS)
1		50%	21	Reduce Net Present Value	●	●	○	●	○	▽	○	●	▽	●	●	▽	▽	○	○	●
2		17%	7	Reduce operational and embeded energy	○	●	▽	○	○	○	○	○	○	○	○	○	○	○	▽	○
3		33%	14	Reduce CO2 emissions	●	○	▽	○	●	○	▽	●	▽	○	○	●	▽	●	▽	○
4	Constraint			Energy-saving standard	●	●		●												
5				Indoor air quality & thermal comfort									▽	○						
6				Illumination											●					
7				Domestic hot water (DHW)								○						○	▽	
Relationships				Technical Importance Rating	800	700	200	600	500	200	233.3	800	133.3	600	600	400	133.3	500	200	600
Strong	9	●		Relative Weight	11%	10%	3%	8%	7%	3%	3%	11%	2%	8%	8%	6%	2%	7%	3%	8%
Moderate	3	○		Weight Chart																
Weak	1	▽		Selected EEMs (x)																

QFD matrices consist of performance requirements (in columns) and properties of EEMs (in rows). The requirements are weighted, depending on their importance, by the pairwise comparison matrix. The correlation between the EEMs and requirements is estimated on a scale of 0, 1, 3, or 9. In this matrix, 9 represents a strong correlation, 0 means no correlation (the blank space in the matrix). In the QFD table, numeric values of the properties are summarized at the bottom of the table by multiplying the correlations and their weights. The user can then select the EEMS with higher values, where higher values indicate higher priorities.

4) System output

A set of potential retrofit measures has been chosen from the QFD matrices and an analysis of their technical correlations in the existing building. Four lists of the relative importance to each EEM defined by the four groups were assembled. In this case study, the importance of the four groups were considered as equal (Table 4.10 on the following page). Ten EEMs were selected and these EEMs have been be transformed into design variables for the optimization stage in the next procedure.

Note that although energy loss from air infiltration cannot be neglected, the option of improving building air-tightness was not selected. The reasons for this are as follows: first, the replacement of windows will reduce the air-tightness to an acceptable level for office buildings with large shape factors; and second, further improvement of the building air-tightness is achieved by stricter control on the site, and additional work processes require that the workers will need extra training (which is quite difficult).

Table 4.10: Data analysis of the quality function deployment (QFD) matrices for the case study building in China

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Quality function deployment matrices	Insulate external walls	Insulate roof	Insulate ground floor	Glazing insulation with sun shading	Sustainable insulation materials	Improve building tightness	Improve the current district heating system (DHS)	Distributed energy system (e.g. heat pumps, CHP)	New split-type air conditioner	Radiant cooling ceiling	Update lighting system	Building Integrated Photovoltaic (BIPV)	Wind turbines	Solar thermal panel	Electric water heater	Building energy monitoring system (BEMS)	Sum
S1	11%	10%	3%	8%	7%	3%	3%	11%	2%	8%	8%	6%	2%	7%	3%	8%	100%
S2	9%	4%	1%	10%	12%	2%	3%	12%	2%	3%	12%	7%	2%	13%	3%	4%	100%
S3	6%	11%	2%	8%	6%	4%	4%	9%	5%	5%	14%	8%	5%	8%	2%	5%	100%
S4	6%	12%	2%	6%	7%	4%	5%	10%	2%	6%	12%	4%	2%	12%	2%	6%	100%
Constraints	×			×							×						
avg.	8%	9%	2%	8%	8%	3%	4%	11%	3%	6%	12%	6%	3%	10%	2%	6%	100%
Selected EEMs (×)	×	×		×	×			×		×	×	×		×		×	

5) Design variables

The retrofit solutions in this study concern combinations of choices regarding various EEMs. A design variable thus represents the alternative choices of a selected EEM. Once the potential EEMs are identified, the design team defines the design variables accordingly. Based on the QFD analysis, the current study considers ten potential options out of the sixteen candidates (see Table 4.8 on page 57). Note that the amount of design variables is not necessarily equal to the amount of the EEMs. First, some options such as sustainable insulation materials are complementary features of another chosen option(s). Second, some options only have one choice so there is no need to define it as a design variable for further evaluation.

In this study, the selected option of sustainable insulation materials is a complement to the insulation options for exploring the possibility of enhancing building sustainability. The BEMS has to be connected to the municipal management system, and its configuration will be regulated by the Shijiazhuang Municipal Bureau of Construction. The selected radiant cooling ceiling does not have many choices in the local market and most of these choices are very similar, so we assume that it is also a fixed option.

In many cases, solar thermal systems can be applied as a supplement of distributed energy systems such as heat pumps and CHP. Solar thermal energy can meet a large proportion of the hot water demand in summer and part of the heating load in winter. Here, solar thermal panels are selected to provide sanitary hot water, using a heat pump or CHP as the auxiliary heating system, which can work automatically according to the set time and set temperature and supply constant hot water when needed. Flat plate collectors are the most common type of collector for office buildings. The rated power of the solar kits will be calculated according to the sanitary hot water needs, and it is not necessary to have multiple choices.

Each design variable will have a feasible range of options. For instance, a design team will define a set of external wall insulations with different properties (e.g., insulation material, thickness, and cost). The entire set of design variables with their feasible regions comprises the design space that will be explored in the optimization model. Based on the above analysis, the current study considers seven design variables: insulation types of the exterior walls (Phase 1 and Phase 2) and the roof, the types of windows, distributed energy systems, lighting systems, PV systems, and solar thermal panels. Tables 4.11 to 4.17 present the seven design variables and their properties. Multiple insulation types for the external walls are described in Table 4.11 on the following page (Phase 1, 1987) and Table 4.12 on the next page (Phase 2, 1993). Seven insulation types for the roof are described in Table 4.13 on page 63. Table 4.14 on page 63 presents four types of windows. Energy systems (with cooling), lighting systems, and PV systems are shown in Table 4.15 on page 63 to Table 4.17 on page 64, respectively. The currency used here is the Chinese Yuan (CNY; 1 CNY = 0.16 USD = 0.12 EUR; currency exchange rates as of May, 2014) as the information is based on China's domestic market.

The hourly PV electricity production is simulated in PV Designer [134], which shows that the maximum energy production is achieved by 37° tilt angle. An annual electricity production

Table 4.11: Characteristics of external wall insulation materials for Phase 1 (year of construction: 1987)

N	Insulation types	Thickness (mm)	U-value (W/m^2K)	Cost (CNY/m^2)	Embodied carbon (kg CO_2-eq/m^2)	Embodied energy (kWh/m^2)
0	XPS (Extruded Polystyrene)	40	0.58	145	5.7	47.8
1		80	0.32	175	11.3	95.5
2		120	0.219	205	17.0	143.2
3		160	0.167	235	22.7	191.0
4	EPS (Expanded Polystyrene)	40	0.78	130	4.6	33.0
5		80	0.44	145	9.2	66.0
6		120	0.3	160	13.7	99.0
7		160	0.234	175	18.3	131.9
8	PUR (Polyurethane foam)	40	0.44	160	8.0	45.8
9		80	0.234	205	16.0	91.4
10		120	0.159	250	24.0	137.1
11		160	0.121	295	32.0	182.9
12	VIP (Vacuum Insulation Panel)	20	0.189	220	11.3	211.9

Table 4.12: Characteristics of external wall insulation materials for Phase 2 (year of construction: 1993)

N	Insulation types	Thickness (mm)	U-value (W/m^2K)	Cost (CNY/m^2)	Embodied Carbon (kg CO_2-eq/m^2)	Embodied energy (kWh/m^2)
0	None	0	0.44	0	0	0
1	XPS (Extruded Polystyrene)	40	0.27	145	5.7	47.8
2		80	0.195	175	11.3	95.5
3		120	0.152	205	17.0	143.2
4		160	0.125	235	22.7	191.0
5	EPS (Expanded Polystyrene)	40	0.31	130	4.6	33.0
6		80	0.234	145	9.2	66.0
7		120	0.19	160	13.7	99.0
8		160	0.16	175	18.3	131.9
9	PUR (Polyurethane foam)	40	0.234	160	8.0	45.8
10		80	0.16	205	16.0	91.4
11		120	0.121	250	24.0	137.1
12	VIP (Vacuum Insulation Panel)	20	0.137	220	11.3	211.9

Table 4.13: Characteristics of roof insulation materials

N	Insulation types	Thickness (mm)	U-value (W/m^2K)	Cost (CNY/m^2)	Embodied carbon (kg CO_2-eq/m^2)	Embodied energy (kWh/m^2)
0	PUR	40	0.38	185	8.0	45.8
1		80	0.215	230	16.0	91.4
2		120	0.151	275	24.0	137.1
3	XPS	40	0.48	170	5.7	47.8
4		80	0.29	200	11.3	95.5
5		120	0.203	230	17.0	143.2
6		160	0.157	260	22.7	191.0

Table 4.14: Characteristics of windows (15% broken bridge aluminum frame with a U-value of 0.87 W/m^2K; internal shading on southern and western exposures)

N	Window Types	U-value (W/m^2K)	Effective total solar energy transmittance (%)	Cost (CNY/m^2)	Embodied carbon (kg CO_2-eq/m^2)	Embodied energy (kWh/m^2)
0	Single low e-glazing	4.1	70	450	25.8	86.1
1	Double glazing	2.5	70	760	37.5	127.8
2	Low e-glazing, air filled	1.9	65	860	38.0	157.0
3	Low e-glazing, argon filled	1.3	60	1020	40.3	161.1

Table 4.15: Characteristics of energy systems (with cooling)

N	Energy system types	EF (kg CO_2-eq/kWh)	Heating efficiency (%)	Cooling COP	Cost (CNY/unit)	Energy price (CNY/kWh)	Electric energy production efficiency
0	Gas-fired combined heat and power (CHP)	0.260	69.8	0.9815	1,600,000	0.264	0.245
1	Air source heat pump	0.766	258.6	2.99	804,000	0.740	0
2	Air source heat pump with heat recovery	0.766	269	3.18	1,069,000	0.740	0
3	Ground source heat pump	0.766	384.6	5.3	1,379,000	0.740	0

Table 4.16: Characteristics of lighting systems

N	Lighting Types	Power (W/m^2)	Cost (CNY/m^2)
0	T5 fluorescent lamp with ballast	10.3	13
1	T5 with ballast and reflective fixture	6.9	18
2	LED lamp	3.4	27
3	LED with reflective fixture	2.4	31

of 1179 kWh for a 1-kWp (kilowatt peak) PV panel is achieved according to the simulation.

Table 4.17: Characteristics of PV systems with different covering area, the system will be installed on the roof.

N	Nominal power (kWp)	Cost (CNY/unit)	Embodied energy (kWh/kWp)	Embodied carbon (kg CO_2-eq/kWp)
0	5	58000	104.7	58.5
1	10	103000		
2	20	180000		
3	30	245000		
4	50	425000		

The net energy consumption of sanitary hot water is 25,600 kWh/a based on DIN V 18599 calculations, which means the daily average is 70 kWh. The solar thermal kits are designed to meet the hot water needs on summer days when the kits have the highest efficiency in the year. The DHS does not serve in summer. The yearly energy saving due to the solar thermal kits is 18,000 kWh/a.

4.6 The optimization stage

4.6.1 Objective functions

As is shown in the previous section, three objective functions are identified in the case study: net present value (NPV), annual energy consumption, and annual CO_2 emissions.

NPV measures the project value by taking future cash flows into consideration [135]. It enables comparison of different cost distributions over time and allows for an economic assessment that includes the time value of money. The NPV displays the benefit or loss of delaying (e.g., replacement costs). Future costs are regarded as less important if the inflation rate is lower than the discount rate, and vice versa. The operation time was assumed to be 30 years according to Verbeeck and Hens [136]. Assumptions on further actions, interest rates, and energy price forecast become very uncertain beyond the 30-year time frame. Therefore the NPV is calculated by

$$N = I + \sum_{i=1}^{y} \frac{((Q_h + Q_{hw} - Q_{shw})/\omega_h + (Q_c/\omega_c)) \cdot \eta \cdot (1+r)^i \cdot p + (Q_l - Q_{pv}) \cdot \eta_e \cdot (1+r_e)^i \cdot p_e}{(1+n)^i} \tag{4.3}$$

where N represents the net present value (CNY); I is the initial investment (CNY); Q_h is the annual heating energy demand (kWh/a); Q_{hw} is the annual hot water energy demand (kWh/a); Q_{shw} is the annual solar hot water energy generation (kWh/a); Q_c is the annual energy demand for cooling (kWh/a); Q_l is the annual energy demand for lighting (kWh/a); Q_{pv} is the annual energy generation from PV panels (kWh/a); ω_h is the corresponding heating system efficiency (%); ω_c the cooling system efficiency (%); p is the current energy price of the energy carrier (CNY/kWh); p_e is the current electricity price (CNY/kWh); r_e is the yearly net increase of electricity cost (%); r relates to the energy carrier (%); n is the net discount rate (%); and y is the operation phase (a).

Operational energy and operational carbon emissions are usually taken as measures of energy saving and environmental protection. Past studies have shown that embodied energy and the related carbon emissions in buildings can be considered minor in comparison with the energy used and its consequent carbon emissions during the whole usage stage of a building [137–139]. However, more advanced EEMs have been developed that can reduce the operation energy consumption substantially. More important is that currently numerous materials are available for energy saving, but at the same time more energy is embodied in those materials. Dixit et al. [140] found that the embedded energy has the potential to constitute a big part of the total energy consumption in the life cycle. Therefore, embedded energy and embodied carbon emissions cannot continue to be neglected. The world's leading voluntary energy performance certificate schemes BREEAM, LEED, and DGNB in Germany apply life-cycle assessment (LCA) using different tools for determining an ecological footprint and energy analysis. For example, the ecological footprint of the building is calculated over a life cycle in DGNB. Within the life cycle, four stages are considered (Figure 4.8):

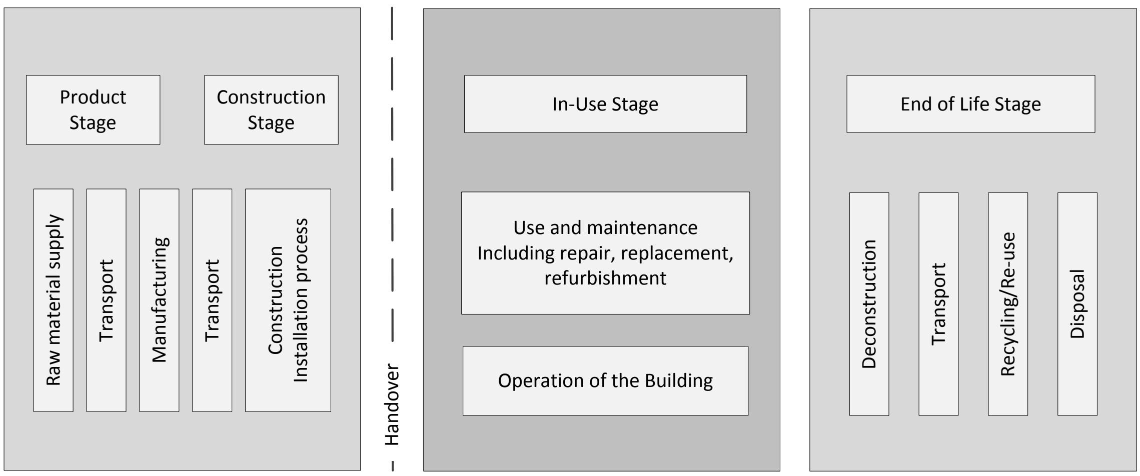


Figure 4.8: Life cycle activities included in DGNB, compiled from [141]. The basic structure corresponds closely to that used in EN15978 for assessment of environmental performance at the building level, with a similar distinction between the same general life cycle activities.

For the case study, the embodied energy and embodied carbon emissions due to the energy retrofit are considered as they are important elements for energy use and environmental impacts. Embodied energy is calculated in the production, transport, and construction stages. The deconstruction stage is not considered because it becomes very uncertain after the 30-year operation period. The values were extracted from the ökobau.dat database [142, 143] and LEGEP [90] since no reliable database for China is yet established. It can be assumed that compared with Germany, the efficiency in China is lower by approximately 40% [144, 145].

Primary energy is taken as the metric for the energy balance to compare different energy sources. In this case study, the annual energy consumption is expressed as

$$Q_{pre} = \sum_{i=1}^{n} a_i Q_i / L_i + ((Q_h + Q_{hw} - Q_{shw})/\omega_h + Q_c/\omega_c) \cdot \eta + (Q_l - Q_{pv}) \cdot \eta_e \tag{4.4}$$

where Q_{pre} represents annual primary energy consumption (kWh/a); a_i is the gross amount of EEMs used in the building (m^2 for the improvements of the façade, kWp for the PV system); Q_i means the embodied energy of EEM i (kWh/m^2 for the improvements of the façade, and kWh/kWp for the PV system); L_i is the life time of EEM i (a); η is the primary energy factor of the energy carrier; and η_e is the primary energy factor of electricity.

The annual CO_2 emissions is expressed as

$$C = \sum_{i=1}^{n} a_i C_i / L_i + (Q_h + Q_{hw} - Q_{shw}) \cdot EF/\omega_h + Q_c \cdot EF/\omega_c + (Q_l - Q_{pv}) \cdot EF_e \tag{4.5}$$

where C represents the annual CO_2 emissions (kg CO_2-eq); C_i is the embodied CO_2 emissions of EEM i (kg CO_2-eq/m^2 for the improvements of the façade, and kg CO_2-eq/kWp for the PV system); L_i is the life time of EEM i (a); EF is the primary CO_2 emission factor of the energy type used in the energy carrier (kg CO_2-eq/kWh); and EF_e is the primary CO_2 emission factor of electricity (kg CO_2-eq/kWh).

The energy embedded in the existing building components is not considered, and the criterion value does not represent the actual annual energy consumption; however, it can be used to compare different solutions. The values of the factors in these equations are listed in Table 4.18

Table 4.18: The values of factors used in the case study

Factor	Value	Factor	Value
r_e (%)	7	η_e	2.7
r (gas, %)	6	η (gas)	1.1
n (%)	3.25	EF (gas, kg CO_2-eq/kWh)	0.260
p_e (CNY/kWh)	0.740	EF_e (kg CO_2-eq/kWh)	0.766
p (gas, CNY/kWh)	0.264		

The design team also assumed that the energy retrofit will not lead to any 'rebound' effect in the future operation phase [146, 147]. In this case study, the building users are not responsible for the energy cost and are thus not incentivized to react to the energy-savings.

4.6.2 Simulation-optimization approach

To identify the optimal solutions for the case study building, a simulation-optimization approach is established by introducing the objective functions and the design variables into a MOO (multi-objective optimization) model. The modified Excel-based calculation tool for the German standard DIN V 18599 is integrated into the optimization model to calculate the energy-related performance for each run. The external shading device, radiant cooling ceiling, and solar thermal panels (discussed previously) will be applied without alternatives. The total number of combinations of building-envelopes, HVAC systems, lighting systems, and PV systems can constitute up to 378,560 (13×13×7×4×4×4×5) alternative solutions. Aiming to achieve high quality results, 800 simulation runs are performed using a population size of 20 individuals and 40 generations. A set of optimal Pareto solutions will be achieved during the whole process. For more details on the Pareto optimum, go to Section 3.5.1 on page 28.

In order to demonstrate the decision-making transition results from changing the economic indicator, a second simulation process is applied. The economic indicator NPV is changed to initial investment cost. By doing this, the pros and cons of whether to consider future costs are listed and discussed. For ease of comparison, the first simulation case is named Case 1, and the second is named Case 2.

4.6.3 The optimized concepts

All the simulations in Case 1 are shown in Figure 4.9 on the next page. In this optimization, 24 Pareto optimal solutions are identified. It can be seen that the values of the three objective functions have great variety over large scales. The value of the net present value (NPV) ranges between 4.6 and 7.4 million CNY; the annual primary consumption ranges from 130,000 to 650,000 kWh; and the annual CO_2 emission ranges from 8000 to 180,000 kg. However, for the optimal solutions, these values are 4.6 to 4.9 million CNY, 130,000 to 170,000 kWh, and 8,000 to 50,000 kg, respectively. The Pareto optimal solutions are clustered together in the very front region of the whole solution space (see the red circle in Figure 4.9 on the following page), where they outperform most of the other alternative solutions (the blue dots) in terms of the three objectives. This means that in this case study the financial, energy-saving, and environmental objectives are not always conflicting.

A further investigation of the three-dimensional Pareto plot is performed using 2D projections of the Pareto optimal solutions in the red circle. Each 2D projection shows the trade-off between two of the three objectives. The Pareto optimal solutions, marked with green dots, are not dominated by any other solutions (Figure 4.10 on the next page), but some optimal solutions in the third projection seem to be suboptimal as they have higher annual CO_2 emissions and higher annual primary energy consumption. This is because that three objectives (net present value, annual primary energy consumption, and annual CO_2 emissions) are treated simultaneously, whereas each projection only shows two objectives. In fact, they are part of the trade-off curve. Table E.1 on page 121 shows all the Pareto optimal solutions and the corresponding values in the three-dimensional criterion space, in which x_1 and x_2 represent the variables of the external wall insulation materials for Phase 1 (year of construction: 1987), and Phase 2 (year of construction: 1993); and x_3 to x_7 represent the variables of roof insulation materials, windows, energy systems, PV systems, and lighting systems, respectively.

The 2D projections show that the optimal solutions are classified into two groups. Group 1 (in the red circle) selects the gas-fired CHP as the heating and cooling system, while Group 2 (in the black circle) selects the ground source heat pump as the energy system. This shows that Group 1 has higher NPV but lower primary energy consumption and lower CO_2 emissions, compared to Group 2. This means that compared with the ground source heat pump, the application of gas-fired CHP is environmentally, rather than financially, optimal. Conversely, comparing the optimal solutions to the solutions that apply to the other two energy systems (air source heat pump with and without heat recovery), both systems indicate better performance both economically and environmentally.

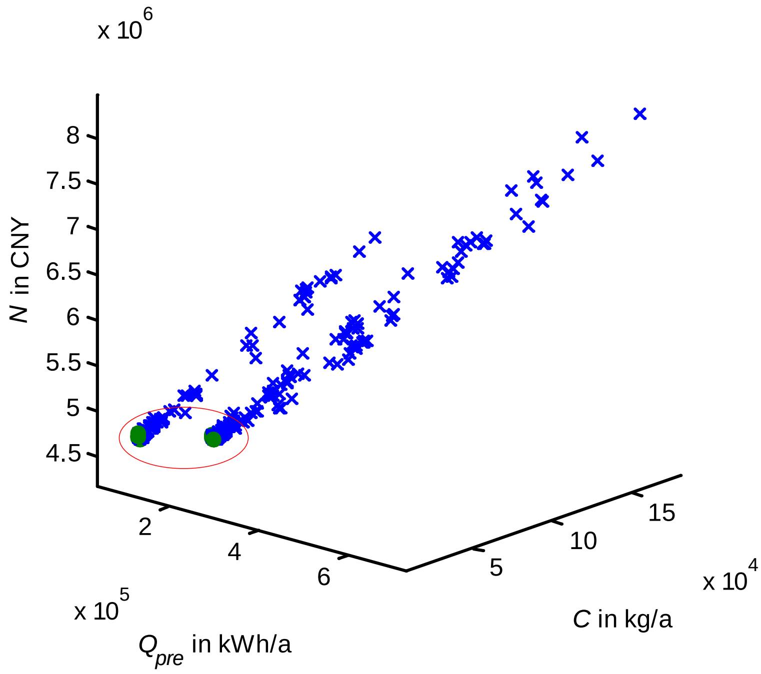


Figure 4.9: The optimization results of Case 1 shown in a 3D space. The green dots in the red curve are the Pareto optimal solutions.

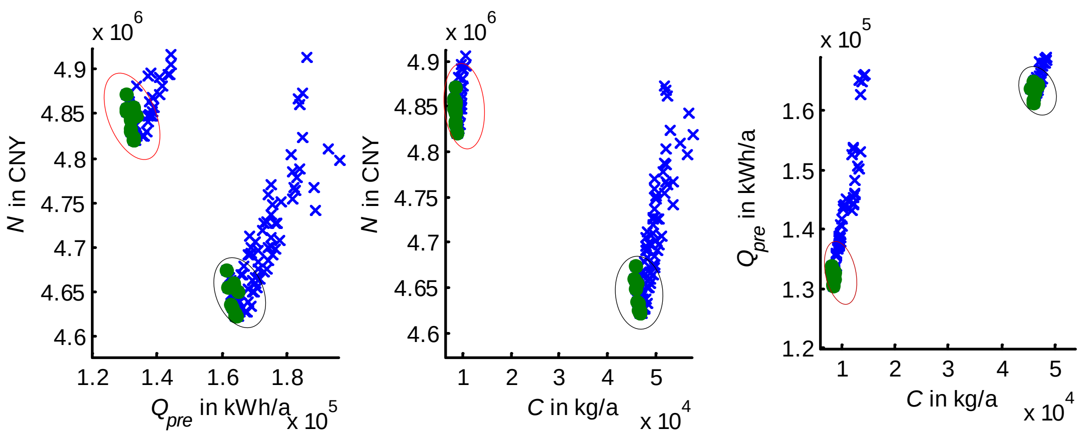


Figure 4.10: The 2D projections of the Pareto optimal solutions (green dots).

The results also show that the PV system with the highest power (50 kWp), and the LED lighting system with reflective fixtures, are listed in all the optimal solutions. This indicates that, both measures contribute to greater reductions in energy consumption and CO_2 emissions, comparatively. It also indicates that they are economically optimal when calculating the total NPV after 30 years. The PV system produces renewable energy for building use and thus helps to reduce energy demand from the urban electricity network. The LED lighting system with reflective fixtures is more energy efficient than the remaining options, and dramatically reduces the energy demand for lighting. Although the initial costs for both are the highest among all the options, the expense saved due to their application in the future operational phase is more significant. The results show that a variety of building-envelope combinations are identified. The low e-glazing, argon filled window, which has the lowest U-value and effective total solar energy transmittance among the four options, is identified as the only choice for all Pareto optimal solutions. The optimal solutions for the walls and roof show that none of the alternatives dominate in all three criteria. The results show that it is recommended to improve the U-values of the exterior wall and the roof to 0.15-0.30 W/m^{2}K, which is economically and environmentally optimal. This is because the costs of insulation materials and labor for building-envelope insulation in China are rather low; when compared to the costs of heating and cooling systems. The overall cost of insulation does not dominate the overall costs, but insulation has a large influence on building thermal performance. Thus insulation is closely related to energy saving, operational cost and environmental impacts.

Based on the optimal solutions, the energy performance level is reduced to 35-45 kWh/m^{2}a of primary energy (excluding energy use of office equipment), while the CO_2 emission level is reduced to 3-12 kg/m^{2}a (excluding carbon emissions from office equipment). An annual electricity generation of approximately 59,000 kWh is realized for a 50 kWp PV system. The total yearly electricity consumption for lighting and devices is much larger (10,000-48,000 kWh/a for lighting based on the simulations, 120,000 kWh for office devices based on the on-site survey) so the PV system will off-set a portion of the electricity consumption. This means that 42.5 kWh/m^{2}a of primary energy use and 13 kg/m^{2}a of CO_2 emissions will be reduced due to the application of a 50 kWp PV system.

Consequently, NPV is an important indicator that helps to identify those EEMs that are comparatively expensive but will significantly contribute to energy efficiency in the building's operational phase. From an environmental viewpoint, applying an energy efficient system reduces the potential operational carbon emissions. Under such circumstances, EEMs such as renewable energy systems and high performance envelopes have a high potential to be selected. In order to show its advantages in contrast to other financial criteria, the next section shows the optimization results when NPV is replaced with the initial investment cost, I.

4.6.4 Initial investment cost as the financial criterion

This section deals with the optimal trade-offs between the initial investment cost I, the annual primary energy consumption Q_{pre}, and the annual CO_2 emissions C. In this esction, representative energy retrofit solutions will be identified and compared them with the optimal solutions obtained in Section 4.6.3 on page 67.

The multi-objective optimization (MOO) model is established in the same manner as that shown in Section 4.6.3 on page 67, and the objective function of net present value, N, is replaced with the initial investment cost I. In the optimization process, 75 Pareto optimal solutions are identified. The value of I ranges between 1.7 and 3.5 million CNY, the value of the annual primary energy consumption, Q_{pre}, ranges from 130,000 to 650,000 kWh, and the value of the annual CO_2 emissions, C, ranges from 8,000 to 180,000 kg. The Pareto optimal solutions have the same ranges as all the alternative solutions, indicating a highly competitive relation between the initial investment cost and the environmental criteria.

Figure 4.11 shows all the simulation results with Pareto optimal solutions marked as green dots. The optimal solutions are also classified into 2 groups. Group 1 (in the red polygon) employs a gas-fired CHP, while Group 2 (in the black polygon) employs an air source heat pump. The 2D projections (Figure 4.12 on the facing page) show that Group 1 has higher initial investment costs but lower primary energy consumption and lower CO_2 emissions compared with Group 2. With an investment cost of 1.6 million CNY, the gas-fired CHP is beyond the economic optimum, but the trade-off is that it is involved in environmentally optimum designs. Compared with Case 1, the economically optimum choice has been changed to an air source heat pump since it is the most inexpensive option among the four choices.

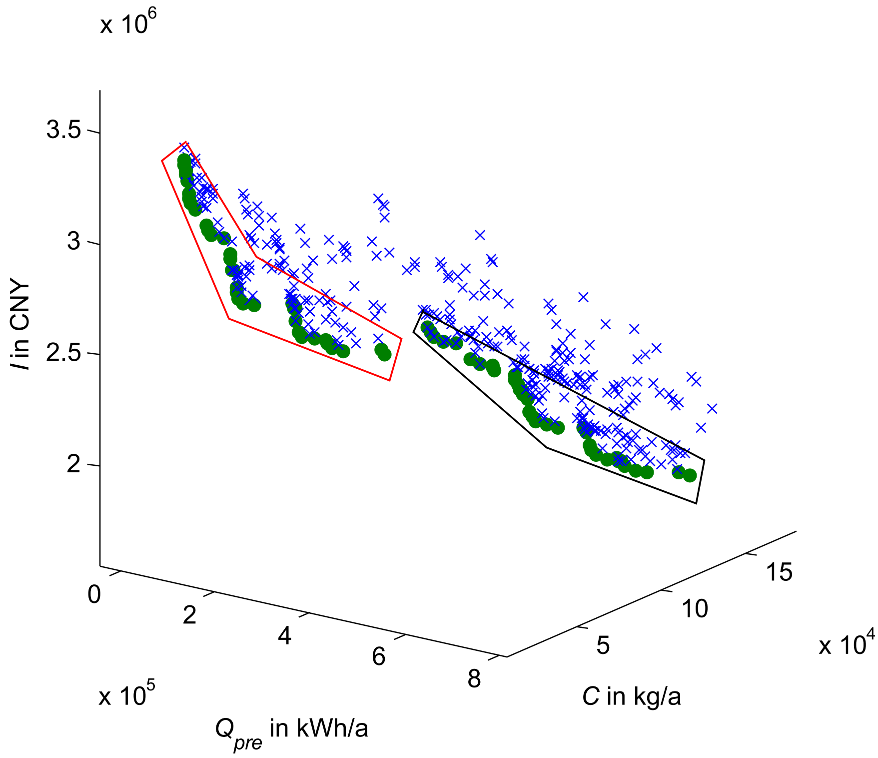


Figure 4.11: The optimization results with the optimal trade-off between the initial investment cost, the annual primary energy consumption, and the annual CO_2 emissions. The green dots are the Pareto optimal solutions and they are distributed in the black polygon and red polygon

The 2D projection of energy and CO_2 emissions indicates that when the heating and cooling system is fixed, both objectives have high positive correlation. This is because a major

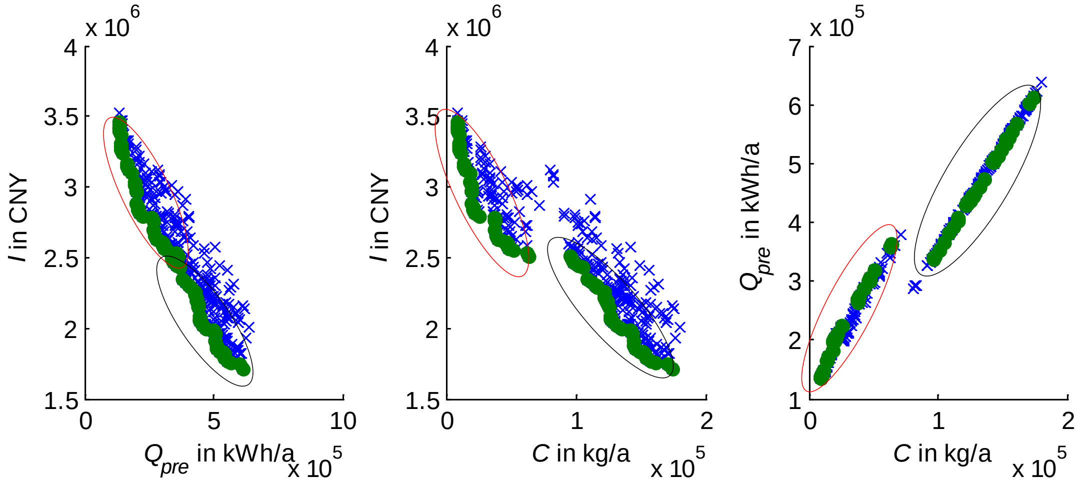


Figure 4.12: The 2D projections of the Pareto optimal solutions (green dots).

portion of operational energy is consumed by heating and cooling systems, whose emission factors depend on the type of heating source and the working processes of the systems. The embodied energy and embodied carbon emissions play a minor role since only the applied EEMs are used in the calculation, and these are divided by the 30-year operation phase. The three heat pumps have similar emission factors (according to the manufacturer's information), so the 2D projection only shows two lines: one for CHP and one for the other heat pumps.

Table E.2 on page 122 lists the set of optimal solutions and the their values regarding the three objective functions. Unlike Case 1, several kinds of PV systems and lighting systems are applied in the set of optimal solutions. The same situation occurs for the building-envelope combinations in the optimal solutions, indicating that, as a criterion, initial investment cost as is highly conflicting with energy efficiency and carbon emissions. In summary, Figure 4.13 on the following page and Table 4.19 illustrate the main differences in terms of the ranges of objective function values and the selection of EEMs. Table E.2 on page 122 also indicates that N values for the optimal solutions range between 4.8 and 7.5 million CNY. The range is much larger compared with the N values for Case 1 (4.6-4.9 million CNY). This suggests that some of these solutions will lead to high future costs.

Table 4.19: Comparison between Case 1 and Case 2 for the selection of energy efficiency measures.

	Energy system	PV system	Lighting system	Window
Case 1	gas-fired CHP, ground source heat pump	50 kWp PV system	LED with reflective fixture	low e-glazing, argon filled window
Case 2	gas-fired CHP, air source heat pump	not specified	not specified	not specified

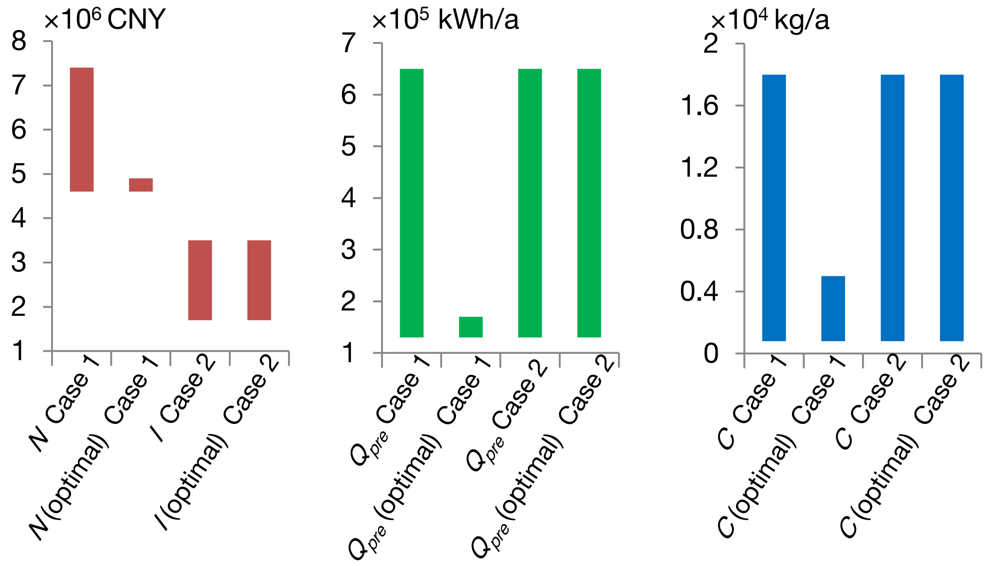


Figure 4.13: Comparison between Case 1 and Case 2 of the ranges of the objective function values. The left chart shows the value ranges of the net present value (N) and initial investment cost (I) of the total solutions and the Pareto optimal solutions in Case 1 and Case 2, respectively. Like-wise the middle and right charts compare the annual primary energy consumption (Q_{pre}) and annual CO_2 emissions C in Case 1 and Case 2.

4.6.5 General findings from the methodology implementation

A fast growing economy and rapidly developing society have led to an increasingly tense situation in China's energy use. To control the growth trend of energy use, strategies at different levels must be used. Currently, the government is advocating for an 'energy-saving and emission-reduction' society, and strict improvements in building performance are certainly a good start. When performing energy retrofits on office buildings in China, not only the current conditions, but also the fact that office buildings are not temporary facilities but provide long-term service, are to be considered. In this situation, both energy use and environmental impact over the operation phase are identified as objectives for retrofit design. As to financial costs, net present value (NPV) shows a great superiority over initial investment cost in that it considers the future costs and thus helps to identify those EEMs that are comparatively expensive but will significantly contribute to energy efficiency and low carbon emissions during the building's operational phase. The results also show a hierarchy of EEMs for the retrofit solution consisting of the following steps in EEM's application.

1. First, to reduce the heating and cooling need for China's ordinary office buildings, a good level of insulation on exterior walls, roofs and windows (with shading) is a very effective measure. The Chinese national standard for building-envelope insulation is not adequate. The results show that recommended U-values for exterior walls and roofs are to be reduced to 0.15-0.30 W/m^{2}K, when taking both economical and environmental factors into consideration. As for windows, effective insulation glazing with shading devices is preferable. In the current

case study, retrofitting the façade eliminates about 70% of its heat loss and cooling need. Compared with replacing heating and cooling systems, insulating the façade is economically more feasible due to the cost advantage of building materials and labor. In the case study, the cost of façade improvement is 30-35% of the total costs. Therefore, the overall cost of insulation does not dominate the total costs, but insulation has a big influence on building thermal performance and thus is closely related to the energy efficiency, operational cost, and carbon emissions.

Air-tightness can be improved during the replacement of windows and doors. Laborers in China's construction field generally lack professional training on air-tightness improvements; hence, it is not advised to make plans for improvements of air-tightness based on the German instructions. However, a remarkable improvement in air-tightness can be expected by the effective replacement of windows.

2. Select an efficient HVAC system, such as a gas-fired CHP or a ground source heat pump. If disconnecting from the district heating system is optional, a more flexible and energy-efficient HVAC system is a good alternative. The initial investment in high performance heating and cooling systems is comparatively high, requiring 40-50% of the total costs in the case study. However, the optimization of net present value (NPV) has shown that such systems are cost-efficient in the long run.

3. The application of renewable energy, especially solar energy, is proven to be economically feasible. Solar thermal systems and PV systems significantly reduce the energy consumption and CO_2 emissions. Solar thermal systems are a cost-effective technology as investment costs are rather low in China. Solar thermal systems can be designed to meet the hot water needs on summer days (when the system has the highest efficiency of the year). The efficiency of PV systems largely is largely related to local climates, and installation power is restricted by the area that is available for installation. For cities like Shijiazhuang in one of the cold regions of China, PV systems improve building energy efficiency, and decrease operation costs.

4.7 Conclusion

A systematic approach to energy retrofits for exploring a large range of EEMs is introduced and applied to office buildings in northern China. From the retrofit strategy of the case study, a set of retrofit principles that are generally applicable to the same type of buildings in northern China, where both heating and cooling are required, is presented. The case study is in its preliminary stage, and shows that a large number of EEMs can be effectively explored in accordance with stakeholder requirements by the adapted QFD (quality function deployment) model. The case study is investigated with two different economic indicators so as to make a contrastive analysis. The results show that investing in a good level of insulation on exterior walls, roofs, and windows (with shading) is worthwhile, and an efficient HVAC system is cost-efficient in the long run. The application of renewable energy, especially solar energy, is also cost-efficient. The following subsections will discuss the additional findings of different facets based on the case study.

4.7.1 Net present value (NPV): planning in the long-term

Solutions for energy efficient and low carbon office buildings have been achieved when taking NPV as the cost objective. However, when replacing it with initial investment cost, such solutions can not be reached. In addition, the initial investment cost of the Pareto optimal solutions in Case 1 ranges between 3.2 and 3.5 million CNY. The payback period is around seven years for these solutions. If a short payback period is taken as the only objective, these solutions will not be acceptable. Therefore, the investigation proves that long-term planning is extremely important for energy retrofits in China. Compared with developed countries, the labor costs for construction and the costs for insulation materials are still quite low. It is recommended to first improve the façade when there is not sufficient budget for the initial investment.

The current DHS with coal as the main energy source (which is the main heating measure in northern China), is energy inefficient and leads to large CO_2 emissions. Replacing this with distributed energy systems such as heat pumps and CHP essentially reduces the operational energy consumption and carbon emissions. The initial costs for such systems are usually quite high, but when considered with total NPV as the financial criterion, they are proven to be cost efficient. Renewable energy systems, especially solar energy systems, can also benefit from the NPV analysis.

4.7.2 Embodied energy and embodied carbon emissions

The case study proves that embodied energy and embodied carbon emissions should not be neglected when analyzing the energy efficiency and environmental impacts of proposed retrofit solutions. During the decision-making process, building materials and products manufactured locally should be considered first to dramatically decrease the environmental impact of transportation; products made from recycled low emission materials are preferable. However, China's industry is still relatively energy-intensive and highly polluting. It is estimated that compared to Germany, efficiency in China is lower by around 40%, leading to high embodied energy and carbon emissions.

4.7.3 Strengths and weaknesses of the methodology

The QFD-based requirement analysis model helps to identify stakeholder requirements and potential EEMs, which are mostly neglected in related studies. The model is designed to be easy to use, as shown in Section 3.4.3 on page 25, and time-saving, with a premise of obtaining rational results for the optimization stage. The MOO model, which is employed to explore the vast trade space of EEMs, is proven to be computationally efficient, and allows for an easy approximation of the Pareto optimal solutions. An optimized concept is researched with the set of Pareto optimal solutions. However, further analysis is still needed to assess the qualities of the optimal solutions for further detailed design. Therefore, as is shown in Figure 3.1 on page 19, other techniques (e.g., MCDM) have to be applied. The theory and application of MCDM is introduced in Chapter 5 on page 77.

Teaching the design team to establish stakeholder requirements and determine potential design options was relatively straightforward. After a 1-day workshop, every participant understood the principles and had learnt how to use the pairwise comparison matrix and the adapted QFD table. It took some effort for the design team to establish the individual model, and most components of the model are set up by the author. The current MOO tool is hard for designers to master; a user-friendly interface (e.g., wizard style) between the model and the user is needed in the future.

Chapter 5

Multiple-criteria decision analysis on building retrofits

5.1 Introduction

Building retrofit designs typically involve a set of complex aspects that must be considered simultaneously. In Chapter 3, a systematic approach to building energy retrofit solutions is proposed. In the integrated MOO process, the generation of a set of tens to hundreds of Pareto optimal solutions is achieved. However, under typical circumstances, only a single or few solutions are chosen for further investigation and development. Therefore, the benefit of this approach can only be realized if these optimal solutions are compared and analyzed in a manner that aids the selection of design solution(s).

Here, a solution analysis procedure to compare and select Pareto optimal solutions from the MOO process for further detailed design is introduced. A model that allows stakeholders to evaluate the potential optimal solutions by considering multiple stakeholder preferences is proposed in this chapter. In the following sections, a multi-criteria decision analysis model is established accordingly and applied to the case study in northern China (Chapter 4 on page 41).

5.2 Structured evaluation in retrofit design

The traditional side-by-side comparison of alternative solutions is not sufficient to identify the optimal alternative when considering multiple criteria. MCDM methods manage multiple quantitative and qualitative criteria to evaluate a set of alternatives. In this study, MCDM methods can also be applied to determine preferred solution(s). Suppose there are m solutions A and n criteria C, a MCDM problem can be shown as follows [79]:

$$
\begin{array}{ll}
\text{criteria} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_m \end{array} \\
(weights & \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \end{array}) \\
\text{alternatives} & \\
A = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}
\end{array}
\tag{5.1}
$$

where w is the weight factor for C, and the entity x_{ij} is the solution A_i's performance value regardinf the criterion C_j. Aggregate values or outranking values are obtained to show the preferable solution(s), depending on the principles of the MCDM models.

When applying MCDM methods, it has typically been the designer's task to develop alternatives. However, here the developed appriach enables the generation of alternative solution by solving the MOO problem. In the MOO process, qualitative criteria tend to be avoided, and the number of criteria is normally limited to two to four. However, in the MCDM process, more information can be considered. This means that besides the criteria applied in the MOO process, other more qualitative and quantitative factors can be involved during in the MCDM process.

Based on a survey of MCDM approaches, the analytical hierarchy process (AHP) and the multi-attribute utility theory (MAUT) appear to be applicable to the current context. One of the advantages of AHP is that it offers a formal and logical way to assign weights to the criteria. MAUT deals with both quantitative and qualitative criteria by a utility function $U(x)$ that evaluates the solution x. Utility is an important term in game theory and economics. Utility is used to measure the satisfaction or preferences of consumers. Similarly, the utility function is a way of measuring the desirability of or preference for alternatives [148]. It describes how the scores of the weighted attributes are added and provides an overall integrated score for a particular choice using the weights applied to each attribute consider the user's judgments regarding the relative importance of each attribute. The clarification of alternatives, objectives, and attributes helps design teams understand the process in a holistic manner. In this study, an AHP-MAUT assessment model is proposed for a structured evaluation of retrofit designs. The next section introduces details about how the model is applied and how AHP and MAUT are integrated.

5.3 Framework for multi-criteria decision-making

Figure 5.1 on the next page shows how the AHP-MAUT model fits into the solution analysis procedure following the MOO process. Six steps are included to analyze the Pareto optimal solutions. The AHP-based model identifies the set of criteria and assigns their weights in steps 1, 2, and 3, while the MAUT-based model assigns aggregated values to the alternative solutions and determines the preference orders in steps 4, 5, and 6. The outcome of this framework is the preference order of these alternatives such that the most promising alternatives are selected for further detailed design. Each step is explained as follows.

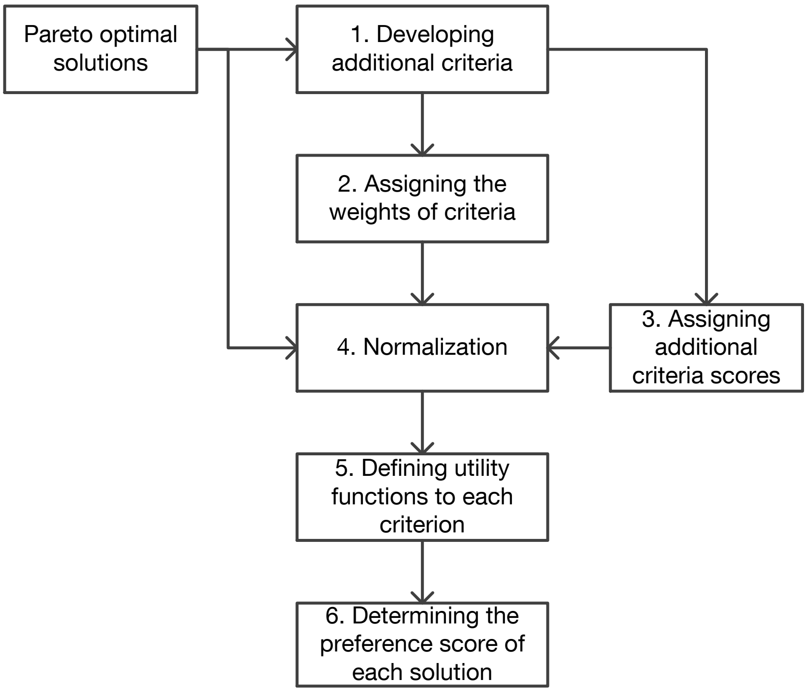


Figure 5.1: Workflow of the proposed AHP-MAUT model

Step 1 is the development of additional criteria. Each optimal solution represents a unique assignment of weight factors of the chosen criteria for the MOO procedure. These criteria are normally incomplete because not every aspect can be quantified, and the objectives in the MOO model are usually limited to two to four to manage computational expense. In the solution analysis procedure, the first step is to consider more information if necessary. The design team evaluates the retrofit project again and identifies the extra criteria (e.g., appearance, functionality) during a meeting after the optimization stage. A hierarchical structure of the criteria is useful to summarize and categorize common concerns among all stakeholders Figure 3.5 on page 22. According to Miller's theory [149], it is wise to limit the total number of criteria to seven because more criteria can lead to partial judgments that do not consider the entire situation.

Step 2 is assigning the weights of the selected criteria. In this step, AHP pairwise comparison matrices are constructed by the design team to assign the weights of the criteria. Participants compare the importance of different criteria to each other, and the results are filled in a square matrix A. The scores of each criterion are then added and normalized to be the final results of the preference. The weighting process is important in that it provides a formal method to compare the criteria and define their relative importance.

It is worth noting that sometimes inconsistencies in the results can occur. For the comparisons of three criteria i, j, and k, if the decision maker evaluates that $a_{ij} > 1$ and $a_{jk} > 1$, then this is an evident inconsistency if $a_{ik} < 1$. Consequently, consistency index (CI) is introduced to check consistency. Discussion of the CI is beyond the scope of this study; however, more information can be found in the literature [80].

Step 3 is assigning grades to the additional criteria. The values of the new quantitative criteria for each solution are calculated based on the variables and the objective functions. When qualitative criteria are chosen, the design team must define a scale for each qualitative criterion to evaluate the performance quantitatively. For qualitative criteria such as appearance and functionality, the design team can assign a grade to each alternative solution based on their preferences in accordance with Table 5.1. Such a process is especially useful in the early design phase, as the design team does not usually possess the skills of MAUT, and a preliminarily assessment on qualitative criteria is acceptable. In this approach, a common measurement scale [150] (Table 5.1) is applied. A 10-grade scale is applied due to its simplicity [24]. The upper end of this scale has a grade of ten, which means that the alternative rates as “excellent”. A grade of four means that the solution is marginally acceptable. The lower band has a grade of zero. This means that the solution performs so badly that it is not acceptable all. It is advised that a solution with a score lower than four should not be considered due to its poor performance and that the chosen alternatives should at least be acceptable (a value no less than four) in the evaluation of each criterion.

Table 5.1: Measurement scale for assigning grades to criteria, adapted from [150]

Grade	Judgment
10	Excellent
9	Good to excellent
8	Good
7	Fair to good
6	Fair
5	Acceptable to fair
4	Marginally acceptable
3	Less acceptable
2	Significantly less acceptable
1	Almost not acceptable
0	Not acceptable at all

In this step, the performance levels of the additional criteria are determined. The evaluation can be based on various methods such as databases, and experience. If no additional criterion is chosen, this step is omitted.

Step 4 is normalization. Normalization helps to mitigate the adverse impacts of different units for different criteria. The minimum and maximum performance of each criterion constitutes the lower and upper ends of the value space. Normalization of a specific value x_i of alternative x is conducted according to $n(x_i) = \frac{x_i - \min(x)}{\max(x) - \min(x)}$, and $n(x_i) = \frac{\max(x) - x_i}{\max(x) - \min(x)}$ when maximizing the criterion.

This step also depends on the manner by which the utility functions are defined (Step 5).

In some cases, a utility function only takes values between 0 and 1. In this case, normalization is required. If the utility function is not constrained between 0 to 1, this step is omitted.

Step 5 defines the marginal utility function of each criterion. The marginal utility function is an expression that relates the preference for the alternatives to a chosen criterion. The shape of the function is defined for each criterion by the design team. Different shapes represent different attitudes about the preferences. In this study, it is assumed that the best case in the alternatives is assigned a score of 1 in the marginal utility function, while a marginally acceptable case from the alternatives is assigned a score of 0.4. The scale is divided into equal intervals (Table 5.2). Here, a linear utility function is one choice; however, it implies that designer preference follows a linear progression, which is not always the case. Other types of utility functions can be used to present different preferences. For example, if investment cost savings are valued more at the highest level, then the utility function shown in the left panel of Figure 5.2 can be applied. Conversely, if differences in the lower part of the savings are more important, a utility function with decreasing marginal utility (middle panel of Figure 5.2) is applied. The right panel of Figure 5.2 describes a situation in which increased value of a function means better results, with a sharpness factor that sets the steepness of the function [151]. As a preliminary evaluation of qualitative criteria, it is acceptable that the design team skips this step if designers do not possess the skills of MAUT.

Table 5.2: Measurement scale for marginal utility functions, adapted from [150]

Utility value	Judgment
1	Excellent
0.9	Good to excellent
0.8	Good
0.7	Fair to good
0.6	Fair
0.5	Acceptable to fair
0.4	Marginally acceptable

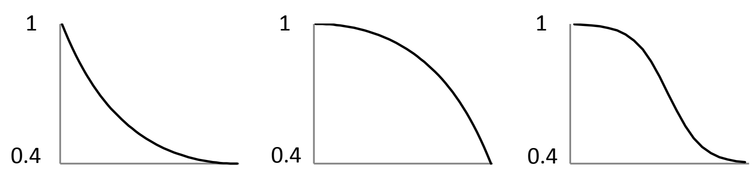


Figure 5.2: Three types of single measure utility functions. The horizontal axes show the attribute value range normalized to zero and one in the previous step, and the vertical axes show the utility value of the attribute. Utility function is an effective way to express nonlinear preferences. For instance, the left function indicates that criteria (e.g., investment cost savings) are valued more at the highest level.

In this step, a radar chart is drawn to illustrate the performance of an alternative relative to the corresponding criteria. Figure 5.3 on the following page shows an example radar chart. Five performance indicators are gathered in one diagram, illustrating the overall performance in a comprehensive manner. The utility value of each criterion is plotted on each axis, with the center of the chart designating the lowest/worst performance and the outer ring the best. However, note that the radar chart does not consider the weight factors; therefore, the shape of a solution does not determine the final preference.

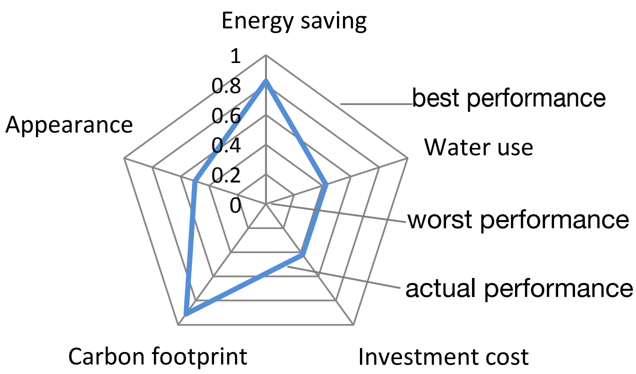


Figure 5.3: A set of five criteria is taken as an example to show the radar chart of a solution. Their utility function values are plotted on each axis. The blue polygon represents the actual performance of the solution regarding the five criteria.

Step 6 determines the preference orders of the alternatives. A utility score is determined by the utility functions of each criterion and weights. The general additive utility function $U(A_i)$ is written as follows:

$$U\left(A_i\right) = \sum\nolimits^{w_j} u_j\left(A_i\right) \tag{5.2}$$

where $u_i(A_{ij})$ is the marginal utility function reflecting alternative A_i's performance on attribute j; and w_j is the importance weight for each criterion assigned by the stakeholders. If the weights are normalized, the utility score of an alternative is always between 0 and 1. The best alternative in this case is that assigned the highest utility score. By allocating utility scores to show preferences, the decision makers can select alternative solutions for the subsequent detailed design.

5.4 Case study

The model was applied to the case study of the office building in Shijiazhuang, northern China Chapter 4 on page 41. The AHP-MAUT model was developed using Matlab, and the radar chart was generated in Microsoft Excel.

The retrofit design of the office building is introduced in Chapter 4. In the design analysis procedure, three criteria, i.e., net present value (NPV), annual energy consumption, and annual CO_2 emissions, are selected and applied in the MOO step. Seven design variables are determined, and 24 Pareto optimal solutions are identified.

At the beginning of the MCDM stage, the design team considered three additional criteria. The initial investment cost, which deals with current investment rather than the future costs, is introduced as a counterweight to the NPV. Functionality and aesthetic appearance are also considered as qualitative criteria. A pairwise comparison matrix was conducted to determine the weights of the five criteria (Table 5.3).

Table 5.3: Pairwise comparison matrix to identify weight factors of the new set of criteria. The 'decimal value' column represents the normalized weight factors.

	CRITERIA WEIGHT	1	2	3	4	5	6	TOTAL	DECIMAL VALUE
1	Initial investment cost	**X**	3.00	1.00	1.00	3.00	3.00	11.00	**0.26**
2	Net present value	0.33	**X**	1.00	0.33	0.33	1.00	3.00	**0.07**
3	Functionality	1.00	1.00	**X**	1.00	3.00	3.00	9.00	**0.21**
4	Annual energy consumption	1.00	3.00	1.00	**X**	1.00	3.00	9.00	**0.21**
5	Annual CO_2 emissions	0.33	3.00	0.33	1.00	**X**	3.00	7.67	**0.18**
6	Aesthetic appearance	0.33	1.00	0.33	0.33	0.33	**X**	2.33	**0.06**
	COLUMN TOTALS	3.00	11.00	3.67	3.67	7.67	13.00	42.00	**1.00**

The initial investment cost is calculated by an independent module in the MOO model. As to the other two qualitative criteria, the design team decided that the evaluation can be quite general in the early design phase. For the criterion functionality, the design team assigned a grade to each solution based on their performance. When assigning solution scores in the context of functionality, the main concern is the selection of energy systems. The other design variables are either mature measures or identified as the same measures in all Pareto optimal solutions. When determining the functionality of different systems, a core question is: "What is its possible weaknesses which are not evaluated in the other existing criteria?" For instance, does a system have negative impact on the environment other than CO_2 emissions? The design team assigns a score to each solution with a certain energy system according to Table E.1 on page 121. Once again, experts must be involved to make rational judgments. Among all the alternatives, two types of energy systems are involved, i.e., gas-fired combined heat and power (CHP) and ground source heat pump (GSHP). Based on the answers to this question and the ten-point scale in Table 5.1 on page 80, a score of seven is assigned to solutions with CHP, while a score of five is assigned to solutions with GSHP. The main reason for assigning a smaller score to GSHP is that its vertical boreholes may pose threats to the groundwater when the boreholes are not properly grouted.

Unlike the processing method of the criterion functionality, a utility function is defined for the criterion aesthetic appearance. It is mainly to show how MAUT can be applied in the evaluation process. Of particular note is that the evaluation of aesthetic appearance in this context is much simplified. It is assumed that the appearance of the building is improved by adopting the external insulation. However, thick insulation leads to a clumsy appearance, which diminishes improvement. Therefore, the design team assumed that the appearance can be measured by linking the thickness of external wall insulation to the appearance function. A utility function $U_a(x)$ is defined that follows a less-is-better form (Figure 5.4). When the thickness is less than 120 mm, the design team decides that the appearance is above the level of good(a score of 0.8). When the thickness is around 200 mm, a score of 0.4 indicates that it is marginally acceptable.

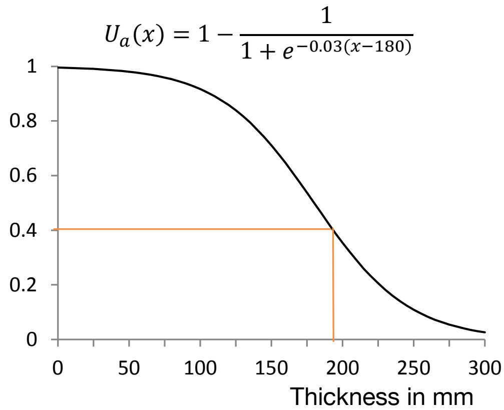


Figure 5.4: Utility function for aesthetic appearance specifically adapted for the case study. The horizontal axis represents the external insulation thickness. The function follows a less-is-better form. A score of 0.4, when the thickness is approximately 200 mm, indicates that it is marginally acceptable.

The four quantitative criteria are minimized according to $n(x_i) = \frac{x_i - \min(x)}{\max(x) - \min(x)}$. The marginal utility function of functionality is defined to take values between four (marginally acceptable) and ten (excellent); thus, the scores remain unconverted in this step.

The next step is to define a marginal utility function for each criterion. The utility functions of the four quantitative criteria are based on a geometric progression scale proposed by Lootsma [150]. Lootsma's theory established a link between a quantitative and a qualitative scale by categorizing quantitative the scale values using verbal expressions, such as acceptable, fair, good, and excellent. A mapping between the normalized score and the utility value is shown in Table 5.4 on the facing page. The marginal utility function of functionality, which follows a linear progression, is shown in table 5.5 on the next page. With regard to aesthetic appearance, a marginal utility function is defined as $U_A(x) = 0.4 \arccos U_a(x_{phase1}) + 0.6 \arccos U_a(x_{phase2})$ such that both Phase 1 (x_1, year of construction: 1987) and Phase 2 (x_2, year of construction: 1993) of the whole building are considered. The factors (0.4 and 0.6) are determined by the external wall area ratio of the two phases.

After carrying out these steps, a utility score for each solution is obtained. The alternatives are ranked (Table 5.6 on the facing page) based on stakeholder preferences. A radar chart (Figure 5.5 on page 86) is applied to show the trade-offs among different criteria for the optimal solution (No. 16) compared to two alternative solutions. As can be seen, the design solution performs well for energy efficiency and CO_2 emission reduction. Its functionality achieves a score of 0.7 due to the application of CHP. The appearance function has a score of 0.91 by applying thinner insulation to the external wall. However, cost efficiency is less attractive in

Table 5.4: Geometric progression scale and corresponding utility scores for quantitative criteria

Normalized score	Judgment	Utility value
0	Excellent	1
0.05	Good to excellent	0.9
0.15	Good	0.8
0.3	Fair to good	0.7
0.5	Fair	0.6
0.75	Acceptable to fair	0.5
1	Marginally acceptable	0.4

Table 5.5: Linear marginal utility function of functionality, adapted from [150]

Score	Judgment	Utility value
10	Excellent	1
9	Good to excellent	0.9
8	Good	0.8
7	Fair to good	0.7
6	Fair	0.6
5	Acceptable to fair	0.5
4	Marginally acceptable	0.4

terms of total NPV. Table 5.7 on the following page lists the EEMs in the solution. The initial investment cost is 3.50 million CNY, and the total NPV is 4.83 million CNY. Its calculated primary energy consumption is 131,000 kWh/a, and the annual CO_2 emissions are 8460 kg. Note that all the solutions with CHP achieve higher utility values than the solutions with GSHP (Table 5.6) due to CHP's higher functionality scores but because application of CHP has inner interactive influences on the other criteria.

Table 5.6: Rank of solutions based on the proposed multi-criteria decision-making (MCDM) model

Rank	No.	Utility value	Energy system	Rank	No.	Utility value	Energy system
1	16	0.736	CHP	13	21	0.703	CHP
2	6	0.735	CHP	14	3	0.666	GSHP
3	4	0.734	CHP	15	1	0.640	GSHP
4	17	0.731	CHP	16	8	0.634	GSHP
5	24	0.727	CHP	17	19	0.620	GSHP
6	9	0.726	CHP	18	5	0.618	GSHP
7	2	0.724	CHP	19	18	0.602	GSHP
8	12	0.722	CHP	20	11	0.597	GSHP
9	22	0.721	CHP	21	13	0.592	GSHP
10	7	0.715	CHP	22	14	0.587	GSHP
11	23	0.713	CHP	23	20	0.573	GSHP
12	10	0.708	CHP	24	15	0.572	GSHP

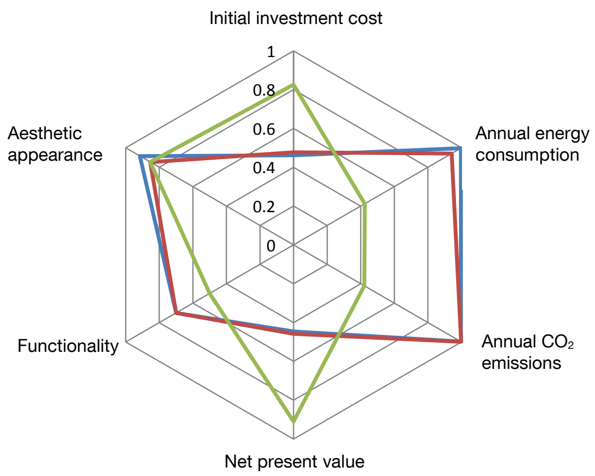


Figure 5.5: Radar chart of the Rank 1 solution (No. 16, blue) compared to solution No. 1 (green) and No. 10 (red).

Table 5.7: Energy efficiency measures in the Rank 1 solution (No. 16)

No.	Energy efficiency measures
1	120 mm Expanded Polystyrene (EPS) insulation for the external wall (Phase 1, 1987)
2	80 mm Polyurethane foam (PUR) insulation for the external wall (Phase 2, 1993)
3	120 mm PUR insulation for the roof
4	Low e-glazing, argon filled windows with external shading on southern and western exposures
5	Gas-fired combined heat and power (CHP)
6	50 kWp PV system
7	LED lighting system with reflective fixture
8	Building energy monitoring system
9	Solar thermal panel for sanitary hot water (18,000 kWh/a)
10	Radiant cooling ceiling

5.5 Conclusion

The research question is based on the previous study that alternative design solutions are the Pareto optima generated by the MOO process. Each optimal solution represents a unique assignment of weight factors of the conflicting objectives. To access the qualities of the optimal solutions, MCDM techniques are applied. The MOO model contains a set of conflicting criteria; however, the design evaluation must often involve more qualitative criteria, which the MOO process tends to avoid because of its high reliance on numerical computations. These qualitative criteria need a preliminarily assessment in the early design stage. Since an MCDM model is concerned with solving decision problems that involve multiple criteria, more information can be considered. The list of criteria could contain not only the predefined design criteria for the MOO model, but also other qualitative and quantitative factors. In this context, solutions from the Pareto frontier are compared and ranked to help the design team make informed decisions about the selection of solutions. Note that decision-makers define the preference relations between pairs of alternatives with respect to every criterion: Thus, stakeholder preference and insight remain a significant influence on the final results of the MCDM. Stakeholder preferences must be analyzed again if more factors are to be considered and compared.

The AHP-MAUT model is proposed based on the analysis of the optimization features, and the fact that the design team wants to control the process rather than have the computer simply provide a definite solution. The main point is to help the design team evaluate the solutions according to multiple criteria. The model is applied to the case study introduced in Chapter 4. It shows that with the support of the proposed model, a rational decision-making process is performed and the alternative design solutions are ranked with regard to the diverse stakeholder requirements.

Chapter 6

Uncertainty analysis

6.1 Introduction

As shown in the previous chapters, the proposed model enables the generation of deterministic optimal solutions for the retrofit design. However, real-world construction activities do not behave in a deterministic manner, and most systems behave stochastically – involving variation or probability. A design should not be accepted if it is not reliable and robust, meaning that optimal solutions must not only satisfy the requirements of building performance but also be resilient to the potential deviations of design parameters and constraints. The question is "*will the values of the objective function be completely different if the basic data (e.g., prices, U-values, embodied energy) is slightly wrong?*" Figure 6.1 on the following page shows an example of the uncertainty of design solutions. The blue dots are the Pareto optimal solutions regarding two objectives. The orange circles indicate the possible variations of these solutions. It shows that when taking the uncertainties into consideration, an optimal solution will not be chosen if the possible result deviates from the Pareto frontier dramatically.

Uncertainty analysis is a useful method to check the uncertainty of the design solutions. It is a general concept which is widely applied for a range of purposes [152, 153]. In this study, its purpose is to solve one question: *Is the performance of the optimum solution sensitive to small changes in the original modeling parameters?* Consequently, a Monte Carlo-based uncertainty analysis model is introduced and applied to two case studies. The strengths and weaknesses of the model are also discussed.

6.2 Uncertainty analysis theory

According to Tian [154], uncertainty analysis methods applied in the domain of building performance analysis is categorized into local and global approaches. The essential difference is that a local approach deals with the variations in each individual parameter and assumes a linear correlation between inputs and outputs, while a global approach is focused on the uncertainties of the whole parameter space. When dealing with building energy retrofits, the interac-

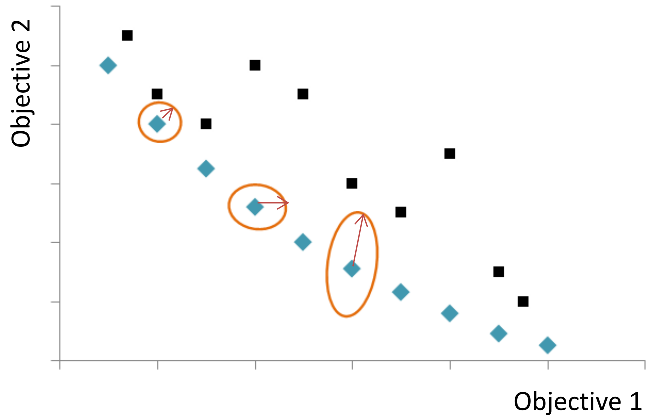


Figure 6.1: An example of the uncertainty of design solutions. The blue dots are the Pareto optimal solutions regarding two objectives. The orange circles represents the possible area that the blue dots will move to. The circles indicate the possible variations of the optimal solutions due to the potential deviations of design parameters and constraints.

tion of the subsystems are important to deal with [102]. These interactions may cause different impacts on building performance when selecting different energy efficiency measures, leading to a nonlinear correlation between design inputs and objectives in many cases. Therefore the global approaches are more suitable for building retrofit analysis. Global methods sample all variables simultaneously. The uncertainty of a specific input parameter is estimated according to its uncertainty mechanism. Typically, a range and a probability density function representing its distribution will be identified. There are several probability density functions for building performance analysis: discrete, uniform, normal, log-normal and triangular [155].

6.2.1 Sources of uncertainties

There are many sources of uncertainties that will lead to the uncertainties of performance outcomes. It is important to identify the sources that matter most to the reliability of the proposed methodology. According to Hopfe et al. [156], there are three types of sources: physical (e.g., material properties, market fluctuations), design (e.g., geometry, infiltration), and scenario (e.g., users' behaviors, operation schemes) uncertainties. Here only uncertainties of the input parameters are considered, as the main task is to test whether the proposed solution(s) is resilient to small deviations of design parameters.

6.3 Methodology: Monte Carlo-based uncertainty analysis

The Monte Carlo analysis (MCA) is an external global analysis method [157]. MCA is able to present statistical analysis results with an arbitrary level of accuracy when provided sufficient number of samples. MCA is widely used in many fields to analyze probabilistic behavior.

To explain the function of MCA, the uncertainty analysis problem with probability theory

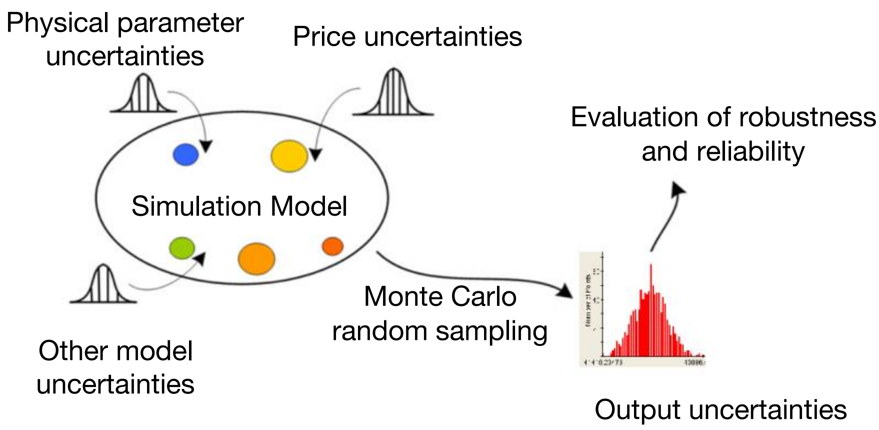


Figure 6.2: Applying Monte Carlo techniques on building performance uncertainty analysis

is firstly stated as a one dimensional problem $y = f(x)$ with y as the output of the computer simulation model. If necessary, it can be easily extended to a multi-dimensional model. When carrying out one experiment, the output y will get a value y_1 because the input x changes to x_1 due to the uncertainty. Likewise, y_2 and x_2 will be obtained in the second experiment. It is reasonable to obtain a cluster of scatterplots after a series of experiments. When the size of the Monte Carlo experiment is big enough (e.g., 1000), a probabilistic distribution of y will be obtained.

The normal distribution is widely used in many fields to describe random variables when the real distributions are hardly known. The normal distribution describes the probability density with a mean of the distribution and standard deviation. The expression of a normal distribution is:

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{6.1}$$

The parameter μ in this definition is the mean or expectation of the distribution, while the parameter σ is its standard deviation. As shown in Figure 6.3 on the next page, the possibility distribution is closely related to its standard deviation σ. About 68% of values drawn from a normal distribution are within one standard deviation σ away from the mean; about 95% of the values lie within two standard deviations; and about 99.7% are within three standard deviations.

The basic MCA procedure with probabilistic uncertainties includes three steps [158] (see Figure 6.2):

Step 1: A set of data points are randomly generated in consistency with the assumed distribution functions.

Step 2: Deterministic simulations are carried out for each data point to get a set of samples. These samples represent the possible output deviations.

Step 3: Analyze the samples. A standard deviation is approximated and the standard error is defined by the design team to measure the uncertainty of the output.

In Chapter 3 on page 17, the case study of the office building in Aachen, Germany is taken

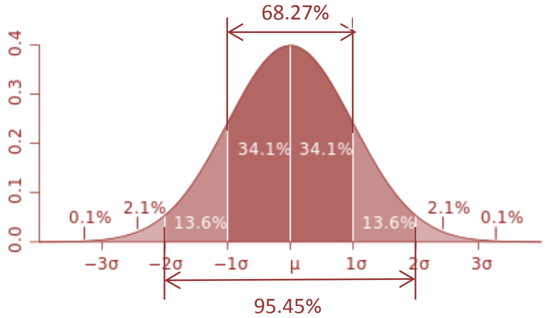


Figure 6.3: The normal distribution and its relationship with standard deviation σ

an example to explain how the developed new methodology is to be carried out. Afterwards the case study in northern China, based on a real energy retrofit project, is done in Chapter 4 on page 41 and Chapter 5 on page 77. Both of the cases will be investigated in the following two sections.

6.4 Case study in Aachen, Germany

In Section 3.6 on page 34, as an example of MCDM, solution No. 76 is identified as the best solution out of the 120 Pareto optimal solutions. According to the design model, solution No. 76 includes 180 mm expanded polystyrene (EPS) insulation on the external walls, 160 mm EPS insulation on the roof, 160 mm EPS insulation on the basement ceiling, high insulation glazing, improvement of the air tightness to N_{50}=1 1/h, and low-temperature boiler for gas combustion. The initial investment cost is € 73,200, the annual operational energy is 42,600 kWh, and the annual GWP emissions are 11,200 kg CO_2-eq.

The purpose of an uncertainty analysis is to test whether the solution is still acceptable when taking the potential uncertainties of the measures into consideration. The process flow is divided into the following steps:

6.4.1 Assignment of normal distributions

Normal distributions are assigned to all uncertain inputs in the case study. As the fluctuations of the energy efficiency measures' prices and physical performances are hard to identify, the standard deviations were assigned in three different sets to allow for a comparison. In the first set, all the standard deviations of the variables were set to 5%, meaning that about 68% of values with uncertainty fall in a range of plus or minus 5% from the mean value, and 95% of the values lie within the range of plus or minus 10% from the mean value. In the second set, these standard deviations were set to 10%, meaning that about 68% of values with uncertainty fall in a range of plus or minus 10% from the mean value. In the third set, the standard deviations were increased to 25% (Figure 6.4 on the next page), indicating the extreme case of uncertainties.

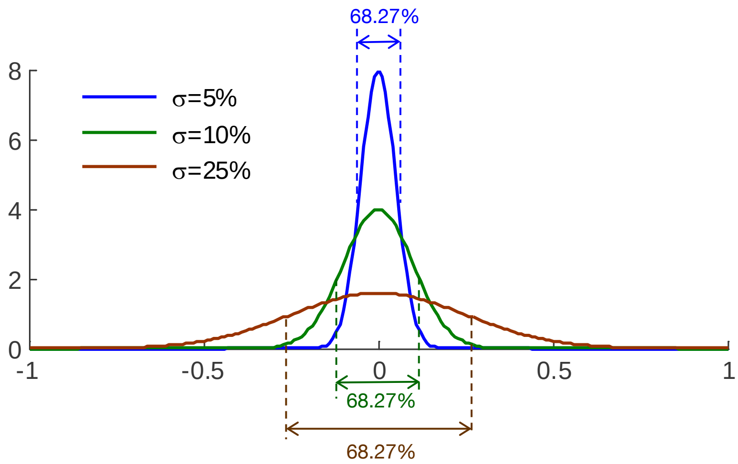


Figure 6.4: The normal distributions with three standard derivations σ are assigned to the selected variables to evaluate and compare the uncertainties.

In the case study, the variables of the energy efficiency measures with uncertainties are: the U-values, window g-value, costs, emission factors, embedded global warming potential (GWP, CO_2-eq. emissions), air tightness, and heating system efficiency. Eighteen variables are taken into consideration.

6.4.2 Integrating Monte Carlo analysis into the deterministic simulation process

An interactive cycle between the Monte Carlo sampler and the building performance assessment model was developed (Figure 6.5). As a start, the sampler generated and sent a set of values to the simulation tools. The model was then executed with these values, and the results of the objectives are stored. The sampler then generated a new set of variable values for the next loop based on Monte Carlo analysis. The whole iteration was not stoped until the last set was carried out. As a result, the distributions of the output are identified based on the simulation results.

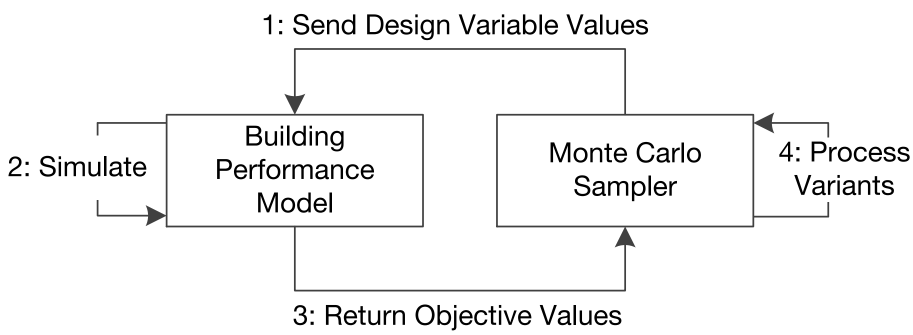


Figure 6.5: The Monte Carlo based simulation process: integration of the deterministic simulation process and Monte Carlo sampler.

For each of the aforementioned two sets, 800 data points were randomly sampled. An example of sampling technique is shown in Figure 6.6.

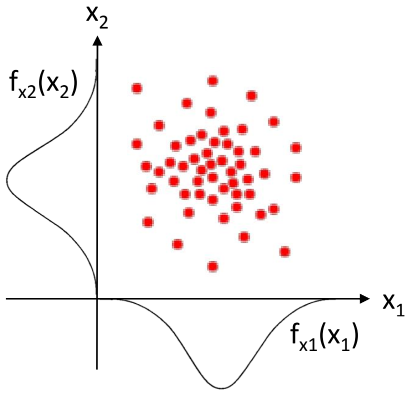


Figure 6.6: An example of the sampling technique: when two variables are sampled, the outcomes are the red data points based on the distributions of the variables.

6.4.3 Result analysis

As is analyzed before, three objective functions were identified in the case study: the initial investment cost, the annual operational energy consumption, and the annual GWP (CO_2-eq. emissions). The distributions of each objective function values are shown in Figure 6.7 (when σ=5%) and Figure 6.8 on the next page (when σ=10%). The corresponding standard deviations were approximated as shown in Table 6.1 on the facing page and Table 6.2 on the next page. In both cases, the mean values are all very close to the original deterministic results, which indicates that the sampling processes are well established.

When the standard deviation for the variables is 5%, the standard deviations for the three objectives are relatively small: the $\frac{\sigma}{\mu}$ of both initial investment cost and annual operational energy consumption are less than 3%. The annual GWP has a larger $\frac{\sigma}{\mu}$(6.8%), but it is still comparatively low.

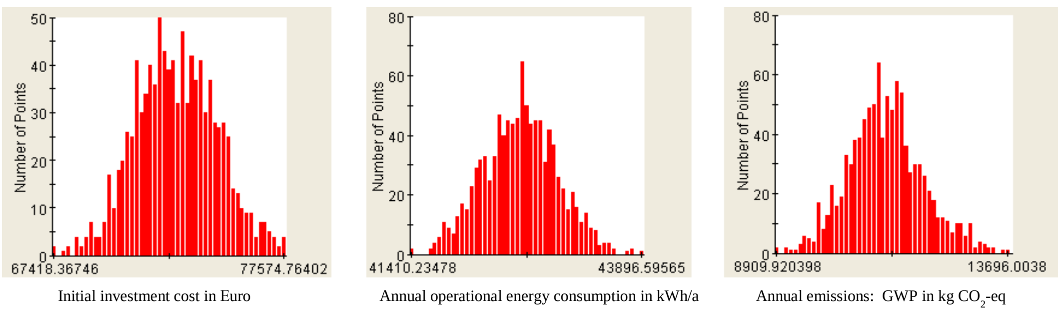
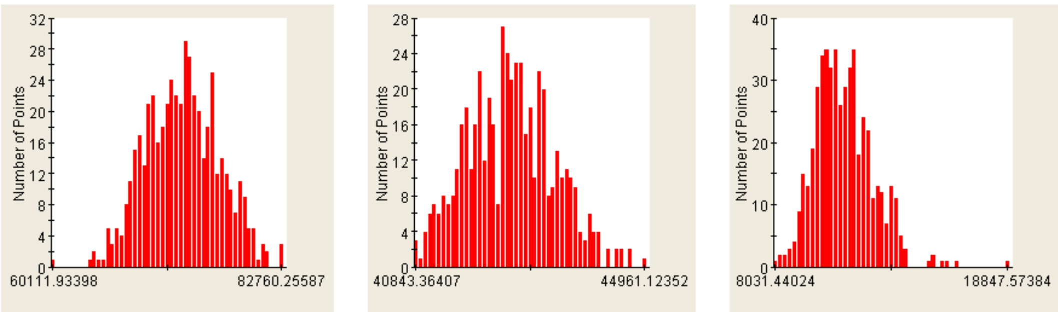


Figure 6.7: The distribution results of the three objective function values, when σ=5%

Table 6.1: The statistical results based on the Monte Carlo analysis, when σ=5%

	Initial investment cost in Euro	Annual operational energy consumption in kWh/a	Annual emissions: GWP in kg CO_2-eq
The original deterministic results	73,200	42,600	11,200
Mean μ	72,800	42,600	11,200
Standard deviation σ	1,786	396	765
$\frac{\sigma}{\mu}$ in %	2.5	0.9	6.8

When the standard deviation for the variables is doubled, the $\frac{\sigma}{\mu}$ of both initial investment cost and annual operational energy consumption are still less than 5%. The annual GWP has a $\frac{\sigma}{\mu}$ of 11.9%, which is still acceptable. It means that when the input data of the design model carefully collected, the chosen solution is stable and acceptable, and the chance to have much higher values in cost, energy consumption and annual emissions is low.



Initial investment cost in Euro | Annual operational energy consumption in kWh/a | Annual emissions: GWP in kg CO_2-eq

Figure 6.8: The distribution results of the three objective function values, when σ=10%

Table 6.2: The statistical results based on the Monte Carlo analysis, when σ=10%

	Initial investment cost in Euro	Annual operational energy consumption in kWh/a	Annual emissions: GWP in kg CO_2-eq
The original deterministic results	73,200	42,600	11,200
Mean μ	7,200	42,600	11,300
Standard deviation σ	3,608	773	1,342
$\frac{\sigma}{\mu}$ in %	4.9	1.8	11.9

A comparison with the extreme case (σ=25% for the design variables) is made in Figure 6.9 on the following page. The standard deviation of the annual GWP emissions will increase to 39% in the extreme case, leading to an unpredictable situation for the proposed solution.

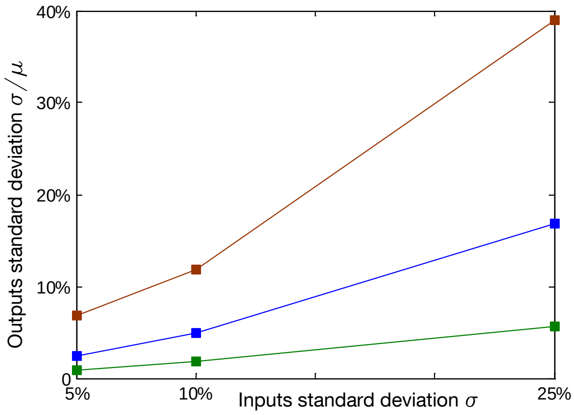


Figure 6.9: The relations between the inputs standard deviation and the outputs standard deviation. The blue dots represent the standard deviation of initial investment cost, the green dots are for annual operational energy consumption, and orange dots are for annual GWP emissions.

6.5 The case study in northern China

As shown in the previous chapters, this case study deals with the retrofit design of an office building in Shijiazhuang in northern China. The MCDM model recommended that the best solution is No.16 out of 24 solutions (see Table 5.7 on page 86). A PV system and a solar thermal panel system are chosen to generate renewable energy, by doing this the deterministic simulation result on the annual CO_2 emissions is only 8,460 kg/a. The corresponding net present value (NPV) and annual primary energy consumption are 4.85 million CNY and 131,000 kWh/a.

The variables of the energy efficiency measures with uncertainties are: the U-values, window g-value, costs, emission factors, embedded CO_2-eq. emissions, air tightness, lighting efficiency, PV efficiency, solar thermal efficiency, and heating efficiency and cooling efficiency of the CHP. In the Monte Carlo sampler, 34 variables are taken into consideration.

Standard deviations of 5%, 10% and 25% were assigned to all the variables separately in three MCA models. After carrying out the same process with the case study in Aachen, the distributions of each objective function values were obtained. Figure 6.10 on the facing page shows the distributions when σ=5%. The corresponding standard deviations were approximated as shown in Table 6.3 on the next page. In this case, the deviations of the objectives due to the uncertainties of the EEMs were relatively low.

A comparison between the three simulations (σ=5%, 10%, and 25% for the design variables) is made in Figure 6.11 on the facing page. The horizontal axis represents the standard deviations σ assigned to the design variables (inputs), and the vertical axis represents the standard deviations for the outputs (blue for annual primary energy consumption, green for annual CO_2emissions, and orange for net present value) from the MCA process. When σ=10, the standard deviations for the three objectives are still acceptable, but they increase dramati-

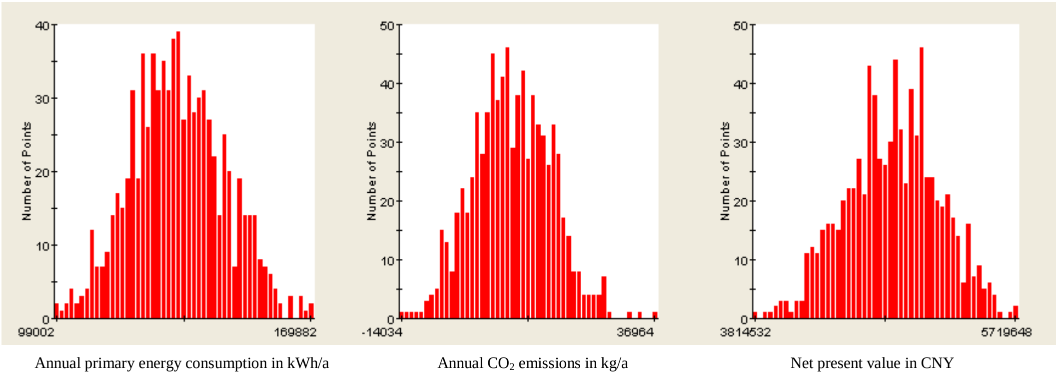


Figure 6.10: The distribution results of the three objective function values, when σ=5%

Table 6.3: The statistical results based on the Monte Carlo analysis, when σ=5%. For the $\frac{\sigma}{\mu}$ of annual CO_2 emissions The standard deviation is divided by the annual CO_2 emissions despite of the contributions from renewable energy.

	Annual primary energy consumption in kWh/a	Annual CO_2 emissions in kg/a	Net present value in CNY
The original deterministic results	131,000	8,460	4,850,000
Mean μ	132,000	8,300	4,820,000
Standard deviation σ	12,540	7,590	339,000
$\frac{\sigma}{\mu}$ in %	9.5	7.8	7.0

cally in the extreme case (σ), leading to an unpredictable situation for the proposed solution.

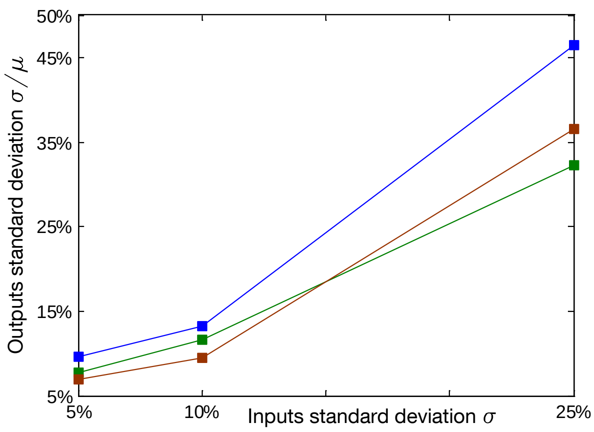


Figure 6.11: The relations between the inputs standard deviation and the outputs standard deviation. The blue dots represent the standard deviation of initial investment cost, the green dots are for annual operational energy consumption, and orange dots are for annual GWP emissions.

6.6 Conclusion

In this chapter, the reliability and robustness of the proposed solutions to the variation of the EEMs' design parameters were quantitatively determined by using a Monte Carlo-based uncertainty analysis. Through the uncertainty analysis, the parameters were assigned normal possibility distributions to simulate the possible fluctuations of the chosen EEMs' costs and physical behavior in the real world. MCA (Monte Carlo analysis) was integrated into the deterministic simulation process to generate the possible variations of the objectives. The benefit of MCA is that it can manage the sampling of multiple variables at the same time. By doing this, the possibility distributions of the objectives are identified and taken as the criterion of reliability and robustness. As the real uncertainty levels of the design variables are not always available, three simulations with different uncertainty levels (small, moderate, and extreme) were made and compared on each case study. Both case studies show that the chosen solutions are very resilient to small deviations (σ=5%, and 10%) in the design parameters, indicating that they are reliable enough to proceed for further detailed design. In the extreme cases (σ=25%), the uncertainties of the proposed solutions are quite high.

Of particular note is that in different cases of building retrofits, it is possible to encounter some design parameters that with a small deviation, the solution's objective values may be significantly changed. Under this circumstance, a sensitivity analysis process before the optimization stage to identify these parameters is of great use [156, 159]. In this case, a judgment on the values of these sensitive parameters is made so that their uncertainties are well handled.

Chapter 7

Discussion

This chapter combines and analyzes the work from the proceeding chapters. The discussions center around the goals defined in the problem statement, in Section 2.4 on page 14. The results show that the developed methodology provides a structured framework to achieve optimal retrofit solutions to enhance office buildings' energy performance and meet the needs of stakeholders. In addition, the limitations of the proposed methodology, revealed in the case studies, are also presented.

7.1 Major findings

In this dissertation, a systematic approach has been developed to support decision-makers in making informed decisions about energy-efficiency solutions in the early design stage of office building retrofits. In contrast to previous approaches, this approach offers an integrated framework to identify the stakeholders' requirements and potential energy efficiency measures, to optimize the large design space, and to determine the optimal solutions, in a holistic way. Mathematical optimization and evaluation techniques are employed into the decision making process, which considers the important role of stakeholders by carrying out the analysis procedure. Case studies have shown the potential of the new methodology in the selection and integration of energy efficiency measures. The proposed methodology and prototype provide guidance to facility managers, engineers and specialized design consultants in collaboration with professional design teams. The major findings from each chapter are discussed in the following passages.

An integrated methodology was proposed in Chapter 3 on page 17, which implements the techniques of requirement analysis, multi-objective optimization (MOO) and multi-criteria decision analysis, and is employed as a whole with all its design and retrofit aspects. The fundamental argument is that when exploring the design space of building retrofits, it is important to address the objective functions, design variables and constraints, according to the characteristics of the building. To capture these characteristics appropriately and to deliver solutions that are useful for for rational decision-making, the interaction with the design team is unavoidable. A comprehensive requirement analysis model involving pairwise comparison and quality function deployment (QFD) was established and embedded in the whole framework. QFD is structured to systematically deal with stakeholder requirements and the engineering characteristics of the design by linking them together. In this study, an adapted QFD approach that supports decision-making on energy retrofits was developed. The ontologies of energy efficiency measures (EEMs) and requirements of stakeholders were discussed to provide adequate consideration of the potential EEMs, objectives and constraints. Later on, EEMs were selected and integrated to generate optimal solutions, which was formulated as a multi-objective optimization (MOO) problem. A non-dominated sorting genetic algorithm-II (NSGA-II)-based optimization model was established, which takes the design criteria, constraints and design variables derived from the requirement analysis model as inputs, and generates optimal retrofit solutions. In most cases, there are dozens, and sometimes even hundreds, of optimal solutions. However, the benefit of MOO models can only be realized if these optimal solutions can be analyzed in a way that aids the selection of design solution(s).Under such circumstances, multi-criteria decision making (MCDM) techniques were applied. The development and applications of the MCDM based analysis model can be found in Chapter 5 on page 77. The example of the office building in Germany illustrated the work process of the whole methodology in this study, in Chapter 3 on page 17.

The implementation of the new methodology was thoroughly examined in the case study on an office building in northern China (Chapter 4 on page 41). This building is representative of office buildings built 20-30 years ago requiring energy retrofits. As was introduced earlier in Chapter 4, it is estimated that in China this type of building comprises more than 95% of office buildings, and more than 70% of total floor area of office buildings. An onsite inspection of the case study building was made first. A design team comprised of architects, civil engineers, mechanical engineers, and the owners was set up to implement the new approach. Several workshops were set up based on the activities defined in the methodology's work process. The result shows that solutions for energy efficient and low carbon office buildings can be achieved when taking net present value (NPV) instead of the initial investment cost as the financial objective. The design team also found that long-term planning is extremely important for the application of high-performance energy efficiency measures in building retrofits in China. In addition, from the retrofit strategy of the case study, a set of retrofit principles that are generally applicable to the same type of buildings in northern China was obtained. First, providing a good level of insulation to exterior walls, roofs and windows (with shading) is a very effective measure. In the case study, it was estimated that retrofitting the façade reduced the total heat loss and cooling need by around 70%. A remarkable improvement in air-tightness can be expected following the effective replacement of windows; however, as laborers in China's construction field generally lack professional training on air-tightness improvements, it is not advised to make plans for such improvements based on the German instructions. Second, an efficient energy system, such as a gas-fired CHP or a ground source heat pump, is cost-efficient in the long run. Third, the application of renewable energy, especially solar energy, is economically feasible and environmentally friendly, thus it is highly recommended for existing office building retrofits.

Building retrofit designs typically involve a set of complex factors to be considered simultaneously. The MOO process in the new approach generates a set of Pareto optimal solutions. However, normally only a single or a few solutions will be chosen for further investigation and development. In chapter 5 on page 77, a MCDM model is developed which allows the stakeholders to better understand and select the potential optimal solutions by taking stakeholders' various preferences into consideration. It contains an analytical hierarchy process (AHP) model to assign weights to additional qualitative and quantitative criteria, and a multi-attribute utility theory (MAUT) model to assess the trade-offs between different solutions by assigning utility values. In this process, a preliminarily assessment on qualitative criteria is also made. The proposed framework was incorporated into the case study in China. In general, the AHP-MAUT model helps the design team to find evaluate the solutions according to multiple conflicting criteria.

Another aspect of building retrofit design is that real-world construction activities do not take place in a deterministic manner, and most systems behave stochastically — involving variation or probability. In chapter 6 on page 89, a Monte Carlo-based uncertainty analysis model was established to address these uncertainties and to investigate the reliability and robustness of the design solutions. Normal distributions were applied in the analysis to describe the random variables, as the real distributions are virtually unknown. As the real uncertainty levels of the design variables are not always available, three simulations with different uncertainty levels (small, moderate, and extreme) are made and compared in each case study. The case studies have shown that the Monte Carlo-based uncertainty analysis model is of great use when addressing the uncertainties of the proposed solutions.

The new methodology provides a platform to facilitate the selectinn and integration of EEMs. Based on this platform, different facets of the decision-making problems were discussed and investigated. In addition, the potential of introducing new technologies to energy retrofit projects through the platform is significant. Stakeholders usually think that high-performance office buildings are less cost effective when there is no reasonable decision support system. The new approach incorporates a structured process to encourage decision-makers to commit themselves to sustainable development. It offers a platform for understanding the opportunities offered by new energy efficiency technologies and thus teaches the design team how best to apply them.

Of particular note is that the developed approach is not a decision maker. It aims to support the designer's decision-making rather than make decisions for the design teams. The case study in China has shown that the design team was supposed to integrate the new approach into the whole inspection and design process. The knowledge and the expertise of the design team remain essential, but the case study has proven that the help of proper decision support methodology that will assist the design team in addressing the problem in its full extent is certainly significant.

7.2 Limitations of the current study

The first limitation of this thesis is that the new methodology relies on the accuracy and availability of the data applied in the process. In order to take a large scope of energy efficiency measures (EEMs) into consideration, efforts to collect the physical, environmental, and economic parameters of these EEMs must be made. For instance, the German LCA database "ökobau.dat" was created with the German building materials industry for determining global environmental effects, but the data from ökobau.dat can not be applied directly into the methodology. A database in the form of a hierarchical structure that contains the related information of EEMs needs to be developed for future applications in the building sector. To achieve this, a lot of efforts must be made.

In the optimization model, the reliability of the embedded simulation and calculation process could be viewed as a limitation, as this process contains different modules to calculate the numerical indicators in terms of the selected design criteria. For different cases, the simulation process can be quite different, and the accuracy relies on these third-party modules such as TRNSYS and EnergyPlus. However, it is necessary to understand that the methodology intends to propose optimal solutions which have relative better performance. The absolute values that an objective function takes, such as annual operational energy consumption, do not matter in this context.

The third limitation is that the new methodology is still limited to research purposes. An integrated computer-based tool with a user-friendly interface between the model and the users has not been developed in this study. Under this circumstance, expertise in the areas of building performance simulation, mathematical optimization and evaluation are required to implement the new approach. The case study in China has shown that teaching a design team on setting stakeholders' requirements and determining potential design options is relatively straightforward. After a 1-day workshop, each participant understood the principles and had learned how to apply the pairwise comparison matrix and the adapted QFD table. However, it took some effort for the design team to establish the optimization and evaluation model, and most components of the model were set up by the author. The current optimization and evaluation tools are hard to master for designers, an user-friendly interface (e.g., wizard style) between the model and the user will be required in the future.

Despite of the above limitations, this study provides a valuable methodology and guidance towards the reaching of energy efficiency solutions that satisfy stakeholder requirements. Based on the findings from the case studies, there is a high potential for the methodology to be applied by a larger group of designers and planners.

Chapter 8

Conclusion and outlook

This chapter first summarized the research conclusions of the whole study, and then proposes the possible development in other circumstances, and further research is also proposed.

8.1 Conclusion

The goal of the doctoral research was to present a new decision support methodology to help designers make informed decisions on choosing the most appropriate design options for retrofitting office buildings with a compromise between stakeholders' diverse and often conflicting requirements in the early design phase. The research efforts have resulted in the following conclusions:

1. In current building energy retrofit projects, most EEMs (energy efficiency measures) are selected in a highly intuitive manner. However, the success of an energy retrofit project is very much related to the selection and integration of EEMs that can satisfy stakeholders' diverse, and often conflicting requirements.

2. In a building energy retrofit project, actual objectives, constraints and requirements are frequently linked to actual design options, and they need to be defined and quantified with the help of proper requirement engineering tools in order for optimal solutions to be found.

3. When exploring the design space of building retrofits, it is important to address the objective functions, design variables and constraints, according to the characters of the building. In order to capture these characteristics appropriately and to deliver solutions that are of interest for the decision-making process, the interaction with the design team is unavoidable.

4. The new methodology developed in this study provides an integrated framework to identify the stakeholders' needs and potential design options, build and optimize the large design space, determine the optimal solutions, and evaluate the design uncertainties, in a holistic way in the early design stage. Beginning with a comprehensive requirement analysis process involving pairwise comparison and quality function deployment (QFD), the stakeholders' requirements and the potential design options are determined by the design team. Later on, a multi-objective optimization (MOO) model is applied to generate a set of optimal solutions.

A multi-criteria decision making process is then carried out, which allows the stakeholders to better compare and select the potential optimal solutions by taking the stakeholders' multiple preferences into consideration.

5. The case study in northern China proves the effevtiveness of the methodology on the selection and integration of energy efficiency measures in the early design phase. In addition, as the chosen building is very representative of typical office buildings built 20-30 years ago that require energy retrofits, a set of retrofit principles that are generally applicable to the same type of buildings in northern China, where both heating and cooling are required, was established.

6. Real-world construction activities do not behave in a deterministic manner. On the contrary, most systems behave stochastically — involving variation or probability. Thus in building retrofit designs, uncertainty analysis is needed to address the design uncertainties and investigates the reliability and robustness of design solutions. In this dissertation, Monte Carlo analysis was integrated into the deterministic simulation process to generate the possible variations of the objectives. By doing this, the possibility distributions of the objectives are identified and taken as the criterion of reliability and robustness.

8.2 Outlook

Apart from applying the methodology during the early design phase of building retrofits, the design of new buildings is also a potential target. The simulation and optimization models are likely to improve the design of the building's components and layouts. In addition, the requirement analysis model can serve to better understand the requirements of the stakeholders. Uncertainty analysis is also important to prevent the new design to be problematic.

Another promising further research topic is uncertainty-based design optimization for building retrofit design. By modeling system uncertainties and coupling them with the simulation-optimization process, it has the potential to generate more reliable and robust optimal solutions [158]. The basic workflow is shown in figure 8.1 on the facing page. The adaptability of uncertainty modeling and Monte Carlo analysis in the whole framework will be investigated in the future research.

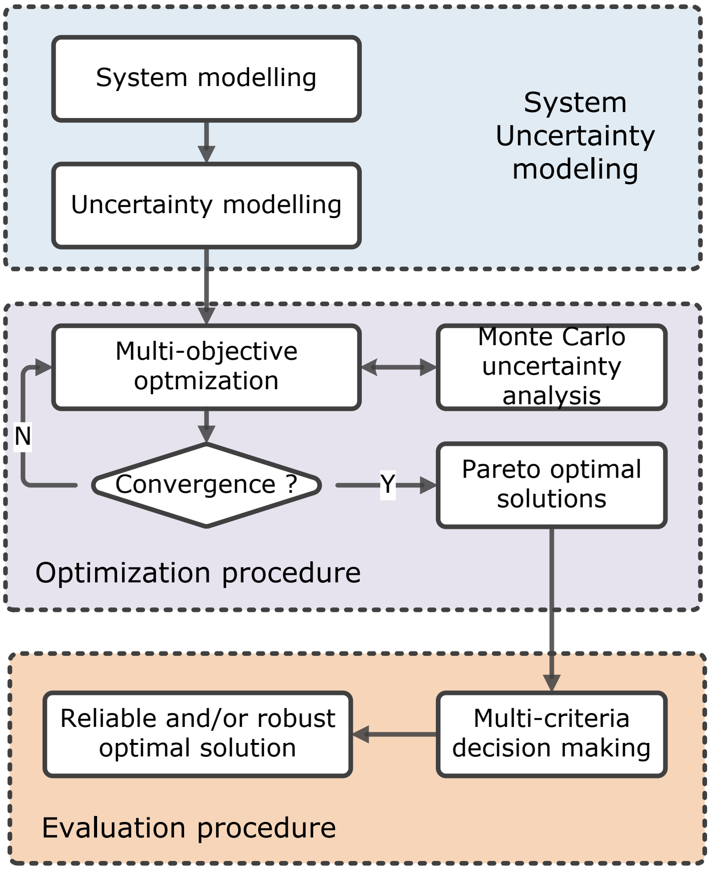


Figure 8.1: The process flow of uncertainty-based design optimization on building retrofits

Appendix A

Optimization results in Chapter 3

Table A.1: Pareto optimal solution of the case study: x_i represents the six design variables described in Section 3.5.2, R_1, R_2, and R_3 represent the initial investment cost in euro, the annual operational energy in kWh/a, and the annual GWP in kg CO_2-eq, respectively.

No.	x_1	x_2	x_3	x_4	x_5	x_6	R_1	R_2	R_3	No.	x_1	x_2	x_3	x_4	x_5	x_6	R_1	R_2	R_3
1	9	14	4	3	0	2	95420	47463	4848	61	11	14	5	3	1	2	100437	44287	4465
2	9	13	8	1	1	3	80172	50026	8098	62	11	12	2	1	2	2	96721	46879	4827
3	10	13	9	2	1	2	95053	47920	4897	63	11	14	6	3	2	3	95026	42624	6604
4	10	12	6	1	2	3	85103	47615	7647	64	9	3	7	1	0	2	87087	50629	5362
5	9	3	6	1	0	2	86806	50808	5379	65	8	3	4	1	0	2	85460	52359	5556
6	10	7	4	3	1	2	99030	45622	4699	66	11	13	6	3	3	3	101305	42324	6540
7	10	4	5	1	1	1	66431	48318	10371	67	10	13	8	3	2	2	103341	44096	4383
8	11	12	0	3	0	2	96740	46669	4785	68	11	14	4	1	0	2	89020	49722	5184
9	9	12	6	1	1	3	80034	49934	8123	69	10	2	8	1	0	1	62822	51159	11120
10	9	13	8	1	0	3	77112	51568	8426	70	9	14	4	3	2	2	102764	44492	4450
11	9	3	7	1	0	1	63087	50629	11012	71	11	8	6	1	1	4	62415	47669	13033
12	10	14	6	1	1	3	81726	48365	7806	72	11	13	4	3	0	4	65667	46351	12452
13	11	7	5	1	2	2	96386	46853	4886	73	6	3	6	0	0	4	52306	58518	16881
14	11	14	5	1	0	4	58277	49429	13578	74	10	13	5	1	0	4	56909	50416	13920
15	8	3	9	1	0	1	62021	52167	11379	75	11	14	4	1	1	1	68080	48194	10265
16	6	3	6	1	0	1	60386	55236	12258	76	11	3	7	3	2	4	73231	42573	11167
17	11	13	11	1	0	4	58784	49432	13541	77	9	2	4	1	0	2	85792	51869	5499
18	7	13	4	1	0	1	61199	53944	11824	78	9	8	6	1	1	3	81714	49117	8039
19	11	12	0	1	0	2	88640	50374	5278	79	11	13	4	3	2	4	73011	43391	11373
20	10	9	6	1	1	3	84129	48033	7838	80	11	8	3	3	1	3	92919	43773	6957
21	11	7	7	3	1	1	76787	44329	9270	81	9	13	7	3	0	4	64809	47112	12713
22	7	4	3	1	0	3	76626	52587	8753	82	9	13	6	3	2	2	102872	44321	4440
23	11	7	4	3	1	3	89945	44981	7172	83	11	1	0	3	0	2	95698	47240	4916
24	9	3	4	1	0	1	62245	51308	11185	84	11	12	9	1	0	2	88675	50296	5228
25	6	13	5	0	0	2	83624	58918	6330	85	11	8	7	1	0	4	59635	49004	13526
26	11	2	6	3	2	4	72498	43298	11416	86	9	12	5	3	0	3	84770	47951	7696
27	8	4	12	1	2	3	84421	48185	7770	87	8	5	7	1	0	3	75916	53415	8909
28	11	14	0	3	0	2	97647	45909	4683	88	10	3	6	1	0	3	77591	50017	8231
29	11	12	0	3	2	2	104084	43725	4391	89	11	14	3	1	1	1	70046	47442	10083
30	11	7	6	3	1	3	90507	44490	7080	90	10	2	6	1	0	1	63138	50585	11002
31	11	6	7	3	2	2	104382	43418	4430	91	11	14	7	1	1	1	68922	47526	10095
32	11	13	0	3	0	2	97194	46210	4723	92	11	8	4	3	0	3	87893	46007	7402
33	9	14	8	1	1	2	90625	49720	5116	93	10	13	6	1	1	2	91273	48680	5039
34	7	3	4	1	0	3	74577	53747	8960	94	9	13	6	3	2	3	92872	44321	6929
35	9	7	7	3	0	2	96027	47228	4915	95	11	4	4	1	2	3	85373	46456	7487
36	11	14	0	3	1	1	76707	44430	9207	96	11	8	4	3	2	1	81237	43065	8903
37	6	3	4	0	0	1	58745	59021	13318	97	10	3	6	3	0	3	85691	46330	7448
38	11	6	6	3	2	3	94102	43587	6877	98	7	2	6	1	0	4	53685	53829	15181
39	11	14	6	1	1	2	92642	47702	4926	99	9	13	6	3	0	4	64528	47287	12770
40	10	14	1	1	0	3	78994	49979	8153	100	11	13	7	3	2	2	104853	42749	4272
41	11	14	8	1	1	2	92326	48278	4959	101	10	2	7	1	2	1	70763	47379	10099
42	9	14	0	3	0	2	95946	47332	4838	102	7	14	4	1	0	4	54652	53623	15029
43	6	3	4	1	0	3	73825	55732	9365	103	7	13	4	1	0	2	85199	53944	5677
44	11	12	6	3	0	3	86775	46303	7387	104	10	2	6	1	0	3	77138	50585	8343
45	8	5	6	1	0	3	75635	53595	8941	105	11	8	5	3	0	3	88150	45721	7347
46	11	14	4	3	2	1	80464	43086	8819	106	11	6	6	3	1	3	89818	45043	7187
47	6	3	4	1	0	4	52825	55732	15853	107	11	3	6	3	1	4	68667	44209	11757
48	11	8	7	3	1	3	91795	43876	6967	108	9	13	7	1	2	3	85053	47779	7670
49	10	4	3	1	0	1	65079	49348	10688	109	10	13	3	1	1	4	61677	48408	13213
50	11	8	6	3	0	3	88455	45500	7307	110	11	4	3	3	2	3	95439	42110	6595
51	10	7	4	3	2	4	72314	44149	11710	111	6	3	4	0	0	4	51745	59021	17051
52	6	3	6	1	0	4	53386	55236	15685	112	10	2	6	1	0	4	56138	50585	14052
53	6	2	6	0	0	2	82853	59091	6424	113	11	3	7	3	0	4	65887	45512	12238
54	10	14	9	3	2	2	104110	43537	4309	114	11	8	5	3	2	1	81494	42786	8830
55	10	7	7	3	1	1	75872	44957	9430	115	11	3	4	1	0	4	56945	49845	13796
56	11	14	1	3	0	1	74009	45638	9558	116	10	13	6	2	1	2	95053	47627	4902
57	9	6	6	1	0	4	55957	51681	14437	117	7	2	4	1	0	2	84124	54333	5793
58	9	4	8	1	1	1	65634	49469	10641	118	11	14	3	3	0	2	99086	45266	4621
59	10	4	3	1	2	1	72423	46336	9834	119	11	14	1	1	0	2	89909	49311	5144
60	9	12	4	1	0	4	55413	51964	14460	120	9	12	6	3	0	4	64074	47739	12935

Appendix B

Interfaces of the applied tools in the methodology

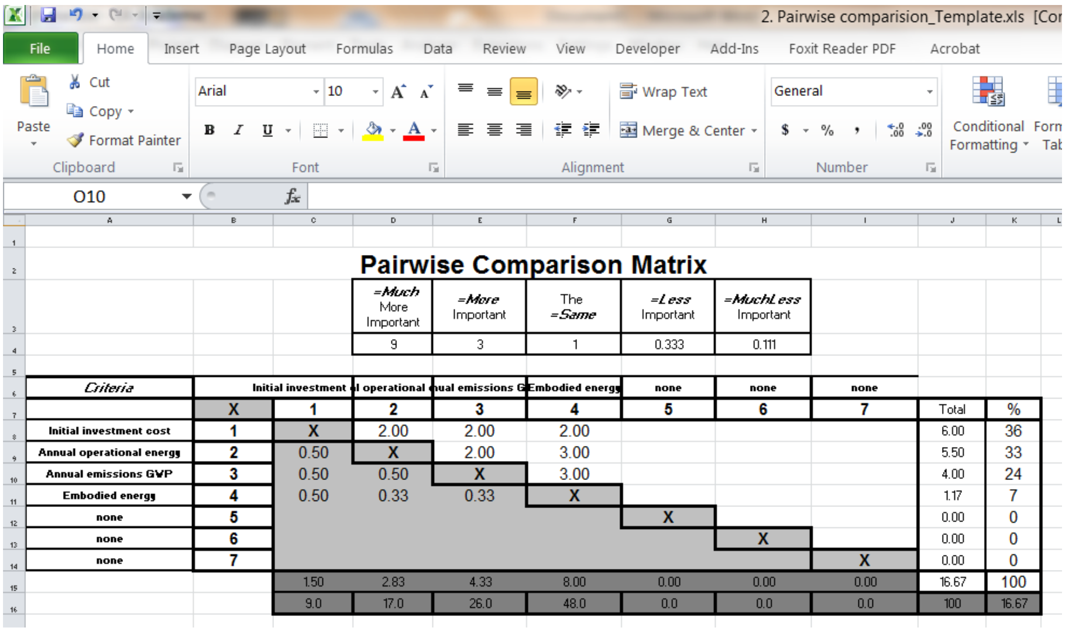


Figure B.1: The interface of pairwise comparison table

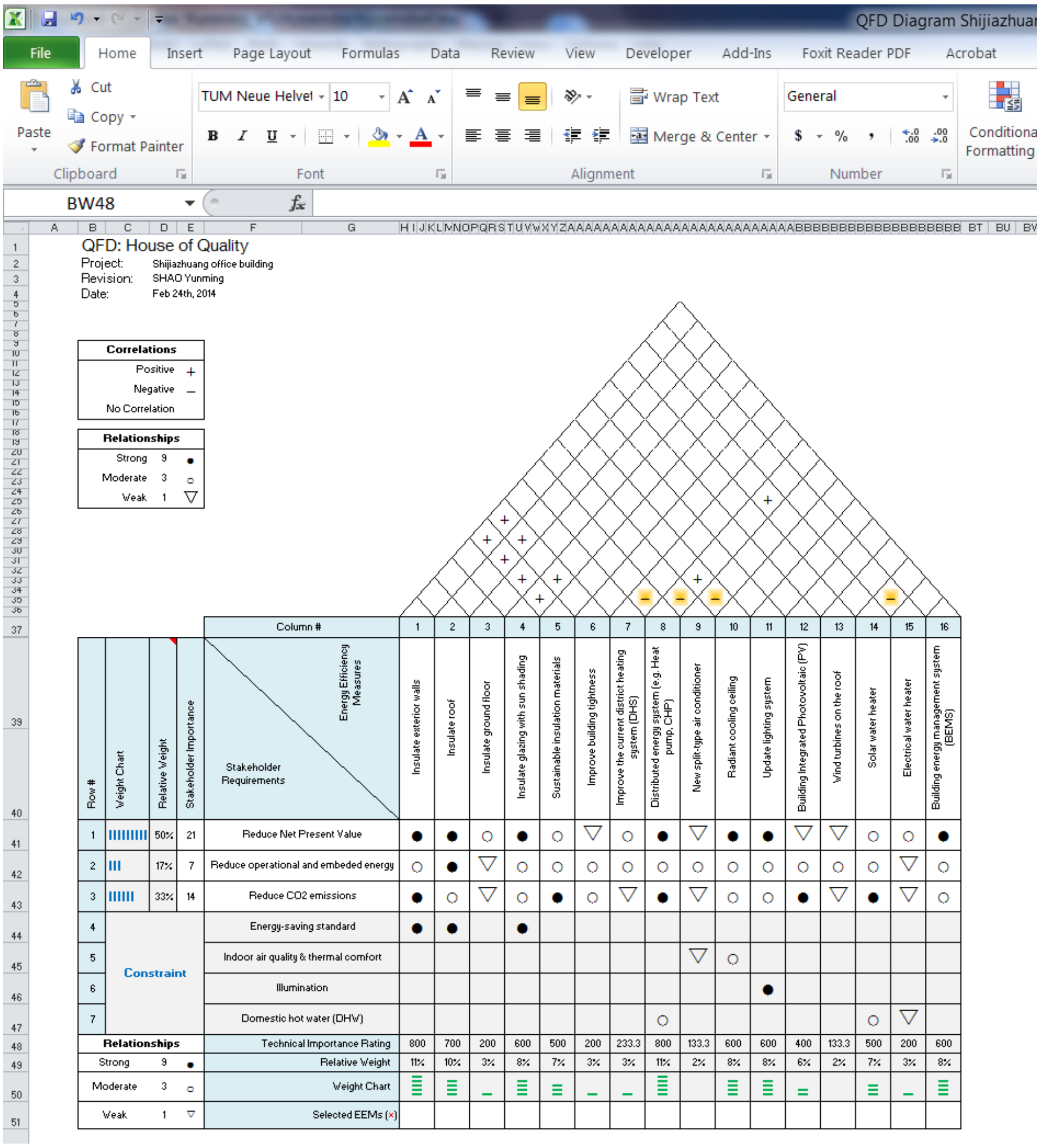


Figure B.2: The interface of quality function deployment table

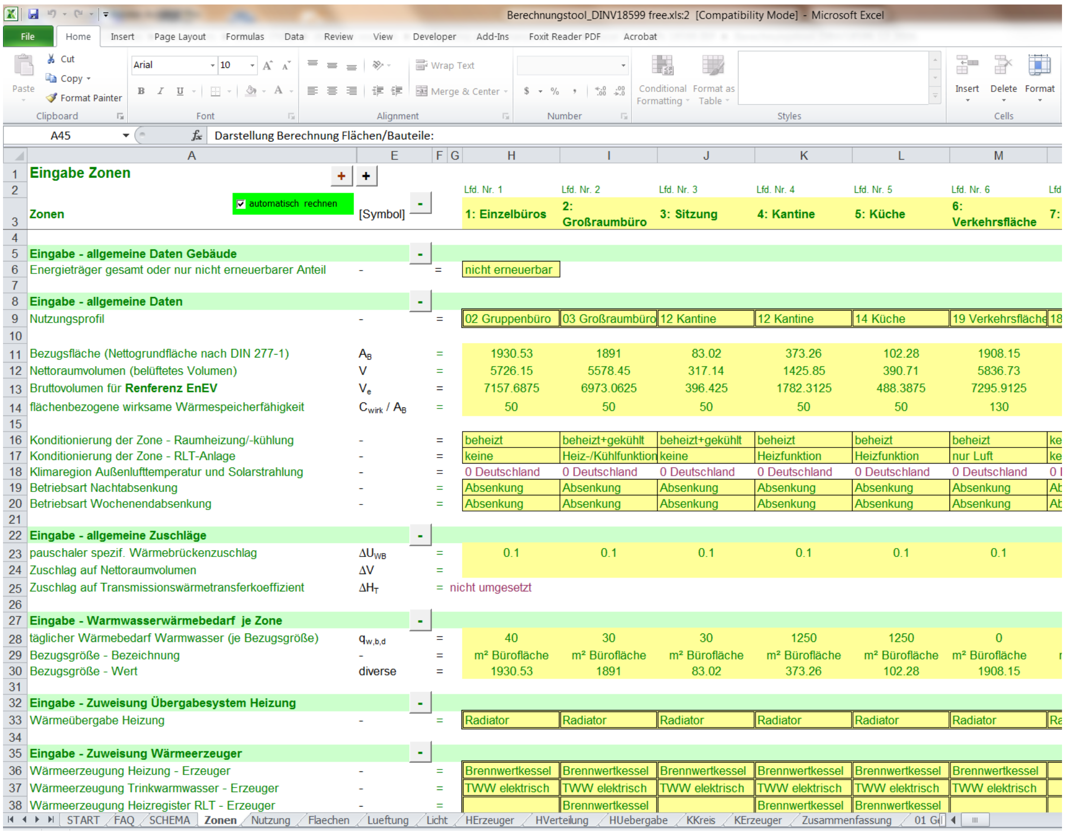


Figure B.3: The interface of energy performance calculator

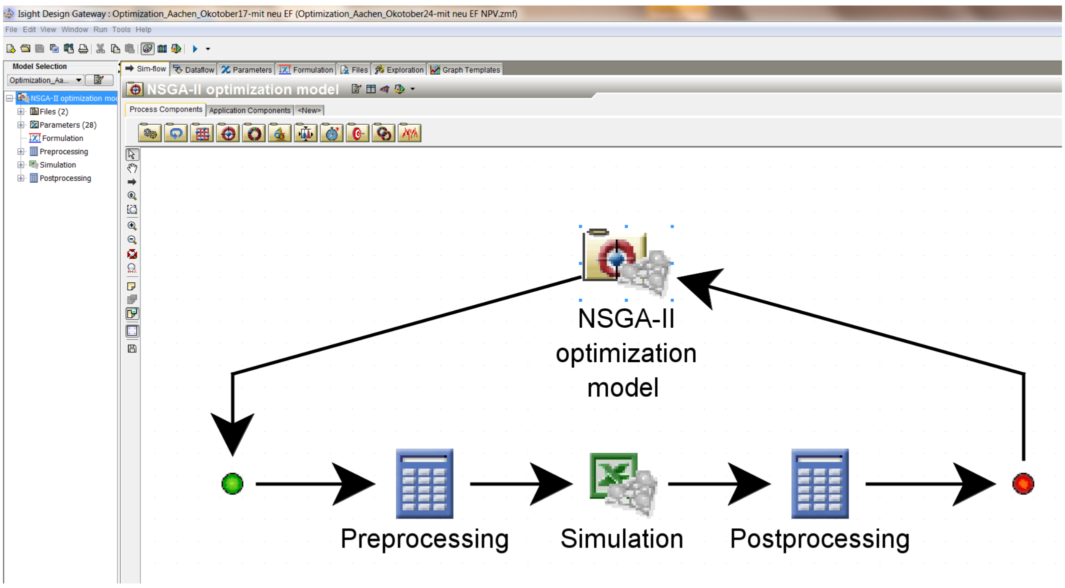


Figure B.4: The interface of the optimizer

Appendix C

Quality function deployment matrices in Chapter 4

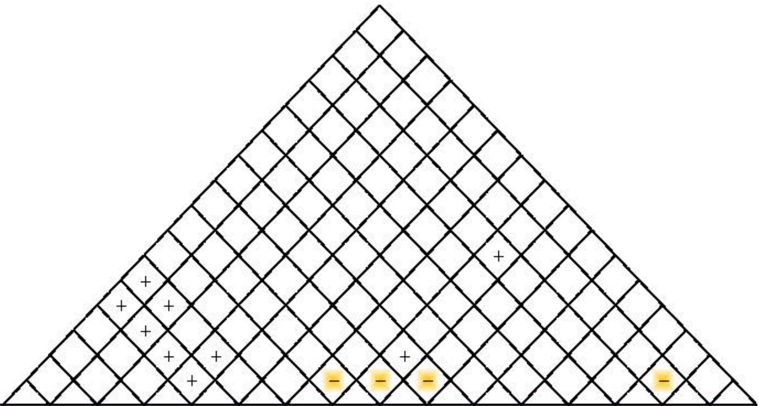
Table C.1: Quality function deployment (QFD) matrix (No. 1)

QFD: House of Quality

Project: Shijiazhuang office building
Revision: SHAO Yunming
Date: Feb 24th, 2014

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships		
Strong	9	●
Moderate	3	○
Weak	1	▽



Row #	Weight Chart	Relative Weight	Stakeholder Importance	Stakeholder Requirements / Energy Efficiency Measures	1 Insulate exterior walls	2 Insulate roof	3 Insulate ground floor	4 Insulation glazing with sun shading	5 Sustainable insulation materials	6 Improve building tightness	7 Improve the current district heating system (DHS)	8 Distributed energy system (e.g. Heat pump, CHP)	9 New split-type air conditioner	10 Radiant cooling ceiling	11 Update lighting system	12 Building Integrated Photovoltaic (PV)	13 Wind turbines on the roof	14 Solar water heater	15 Electrical water heater	16 Building energy management system (BEMS)
1		50%	21	Reduce Net Present Value	●	●	○	●	○	▽	○	●	▽	●	●	▽	▽	○	○	●
2		17%	7	Reduce operational and embeded energy	○	●	▽	○	○	○	○	○	○	○	○	○	○	○	▽	○
3		33%	14	Reduce CO2 emissions	●	○	▽	○	●	○	▽	●	▽	○	○	●	▽	●	▽	○
4	Constraint			Energy-saving standard	●	●		●												
5				Indoor air quality & thermal comfort									▽	○						
6				Illumination											●					
7				Domestic hot water (DHW)								○						○	▽	
Relationships				Technical Importance Rating	800	700	200	600	500	200	233.3	800	133.3	600	600	400	133.3	500	200	600
Strong	9	●		Relative Weight	11%	10%	3%	8%	7%	3%	3%	11%	2%	8%	8%	6%	2%	7%	3%	8%
Moderate	3	○		Weight Chart																
Weak	1	▽		Selected EEMs (x)																

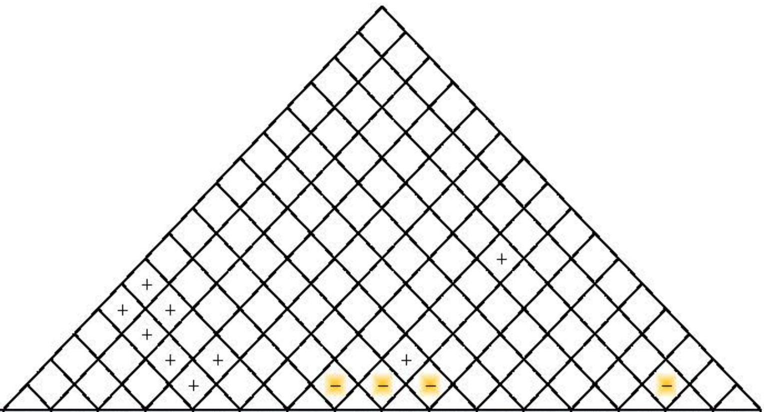
Table C.2: Quality function deployment (QFD) matrix (No. 2)

QFD: House of Quality

Project: Shijiazhuang office building
Revision: De Shengju
Date: Feb 24th, 2014

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships		
Strong	9	●
Moderate	3	○
Weak	1	▽



Row #	Weight Chart	Relative Weight	Stakeholder Importance	Column # / Stakeholder Requirements \ Energy Efficiency Measures	1 Insulate exterior walls	2 Insulate roof	3 Insulate ground floor	4 Insulation glazing with sun shading	5 Sustainable insulation materials	6 Improve building tightness	7 Improve the current district heating system (DHS)	8 Distributed energy system (e.g. Heat pump, CHP)	9 New split-type air conditioner	10 Radiant cooling ceiling	11 Update lighting system	12 Building Integrated Photovoltaic (PV)	13 Wind turbines on the roof	14 Solar water heater	15 Electrical water heater	16 Building energy management system (BEMS)
1		50%	21	Reduce Net Present Value	●	○	▽	●	●	▽	○	●	▽	○	●	▽	▽	●	○	○
2		17%	7	Reduce operational and embeded energy	○	○	▽	●	○	○	○	○	○	○	○	●	○	●	▽	○
3		33%	14	Reduce CO2 emissions	○	○	▽	○	●	▽	▽	●	▽	▽	●	●	▽	●	▽	○
4	Constraint			Energy-saving standard	●	●		●												
5				Indoor air quality & thermal comfort									▽	○						
6				Illumination											●					
7				Domestic hot water (DHW)								○						○	▽	
Relationships				Technical Importance Rating	600	300	100	700	800	133.3	233.3	800	133.3	233.3	800	500	133.3	900	200	300
Strong		9	●	Relative Weight	9%	4%	1%	10%	12%	2%	3%	12%	2%	3%	12%	7%	2%	13%	3%	4%
Moderate		3	○	Weight Chart																
Weak		1	▽	Selected EEMs (x)																

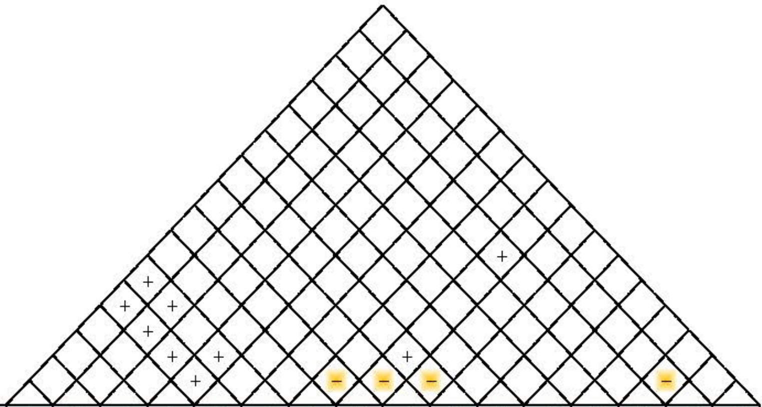
Table C.3: Quality function deployment (QFD) matrix (No. 3)

QFD: House of Quality

Project: Shijiazhuang office building
Revision: Zhang Gaolian
Date: Feb 24th, 2014

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships		
Strong	9	●
Moderate	3	○
Weak	1	▽



Row #	Weight Chart	Relative Weight	Stakeholder Importance	Stakeholder Requirements / Energy Efficiency Measures	1 Insulate exterior walls	2 Insulate roof	3 Insulate ground floor	4 Insulation glazing with sun shading	5 Sustainable insulation materials	6 Improve building tightness	7 Improve the current district heating system (DHS)	8 Distributed energy system (e.g. Heat pump, CHP)	9 New split-type air conditioner	10 Radiant cooling ceiling	11 Update lighting system	12 Building Integrated Photovoltaic (PV)	13 Wind turbines on the roof	14 Solar water heater	15 Electrical water heater	16 Building energy management system (BEMS)
1		50%	21	Reduce Net Present Value	○	●	▽	○	▽	○	○	○	○	○	●	○	○	●	▽	○
2		17%	7	Reduce operational and embeded energy	●	●	○	○	○	○	○	●	○	○	●	○	○	○	▽	○
3		33%	14	Reduce CO2 emissions	○	○	▽	●	●	▽	▽	●	○	○	●	●	○	▽	▽	○
4	Constraint			Energy-saving standard	●	●		●												
5				Indoor air quality & thermal comfort									▽	○						
6				Illumination											●					
7				Domestic hot water (DHW)								○						○	▽	
Relationships				Technical Importance Rating	400	700	133.3	500	400	233.3	233.3	600	300	300	900	500	300	533.3	100	300
Strong		9	●	Relative Weight	6%	11%	2%	8%	6%	4%	4%	9%	5%	5%	14%	8%	5%	8%	2%	5%
Moderate		3	○	Weight Chart																
Weak		1	▽	Selected EEMs (x)																

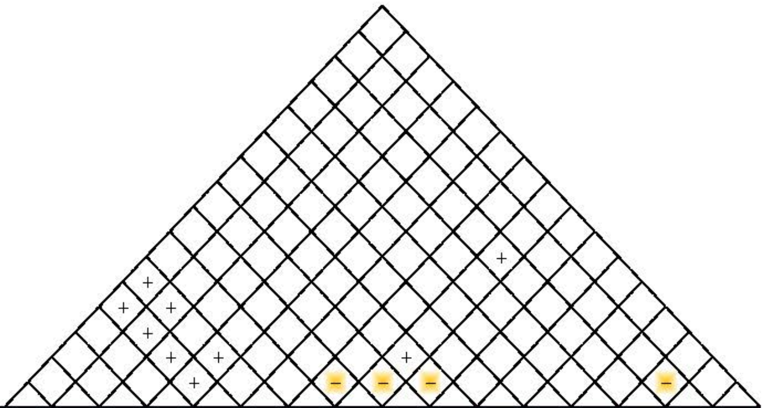
Table C.4: Quality function deployment (QFD) matrix (No. 4)

QFD: House of Quality

Project: Shijiazhuang office building
Revision: LI Wie
Date: Feb 24th, 2014

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships		
Strong	9	●
Moderate	3	○
Weak	1	▽



Row #	Weight Chart	Relative Weight	Stakeholder Importance	Stakeholder Requirements \ Energy Efficiency Measures	1 Insulate exterior walls	2 Insulate roof	3 Insulate ground floor	4 Insulation glazing with sun shading	5 Sustainable insulation materials	6 Improve building tightness	7 Improve the current district heating system (DHS)	8 Distributed energy system (e.g. Heat pump, CHP)	9 New split-type air conditioner	10 Radiant cooling ceiling	11 Update lighting system	12 Building Integrated Photovoltaic (PV)	13 Wind turbines on the roof	14 Solar water heater	15 Electrical water heater	16 Building energy management system (BEMS)
1		50%	21	Reduce Net Present Value	○	●	▽	○	▽	○	○	○	▽	○	●	▽	▽	●	▽	○
2		17%	7	Reduce operational and embeded energy	○	○	▽	○	▽	▽	○	○	▽	○	○	○	▽	○	▽	○
3		33%	14	Reduce CO2 emissions	○	○	▽	○	●	▽	▽	●	▽	○	○	○	▽	○	▽	○
4	Constraint			Energy-saving standard	●	●		●												
5				Indoor air quality & thermal comfort									▽	○						
6				Illumination											●					
7				Domestic hot water (DHW)								○						○	▽	
Relationships				Technical Importance Rating	300	600	100	300	366.7	200	233.3	500	100	300	600	200	100	600	100	300
Strong		9	●	Relative Weight	6%	12%	2%	6%	7%	4%	5%	10%	2%	6%	12%	4%	2%	12%	2%	6%
Moderate		3	○	Weight Chart																
Weak		1	▽	Selected EEMs (x)																

Appendix D

Reference climates

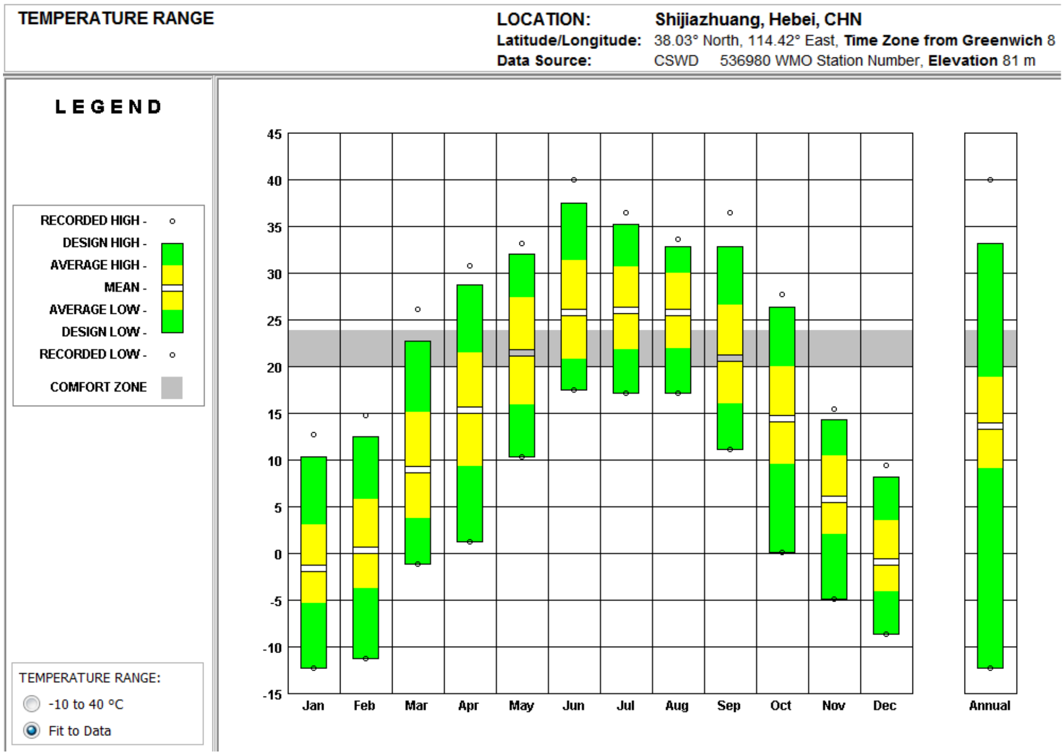


Figure D.1: The temperature range of Shijiazhuang, China.

Table D.1: Solar irradiance and outdoor temperatures of the reference climate of Germany, adapted from [128]

Orientation	Incli-nation	Mean monthly solar irradiance I_s W/m^2												Annual value kWh/m^2
		Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan to Dec
Horizontal	0°	33	52	82	190	211	256	255	179	135	75	39	22	1 120
South	30°	51	67	99	210	213	250	252	186	157	93	55	31	1 216
	45°	57	71	101	205	200	231	235	178	157	97	59	34	1 187
	60°	60	71	98	190	179	203	208	162	150	95	60	35	1 104
	90°	56	61	80	137	119	130	135	112	115	81	54	33	810
South-east	30°	45	62	93	203	211	248	251	183	149	87	49	28	1 177
	45°	49	64	92	198	200	232	236	175	148	88	51	30	1 142
	60°	49	62	88	185	182	208	213	161	140	85	51	30	1 063
	90°	44	52	70	140	132	146	153	120	109	69	44	26	809
South-west	30°	45	62	93	203	211	248	251	183	149	87	49	28	1 177
	45°	49	64	92	198	200	232	236	175	148	88	51	30	1 142
	60°	49	62	88	185	182	208	213	161	140	85	51	30	1 063
	90°	44	52	70	140	132	146	153	120	109	69	44	26	809
East	30°	33	51	78	181	199	238	240	170	129	72	38	21	1 062
	45°	32	49	74	172	187	221	224	160	123	69	37	20	1 002
	60°	30	46	68	160	171	201	205	148	114	65	35	19	923
	90°	25	37	53	125	131	150	156	115	90	51	28	15	713
West	30°	33	51	78	181	199	238	240	170	129	72	38	21	1 062
	45°	32	49	74	172	187	221	224	160	123	69	37	20	1 002
	60°	30	46	68	160	171	201	205	148	114	65	35	19	923
	90°	25	37	53	125	131	150	156	115	90	51	28	15	713
North-west	30°	22	39	63	151	180	222	221	150	105	57	28	16	918
	45°	20	35	56	132	158	194	194	133	91	51	26	14	808
	60°	18	32	49	116	139	168	170	118	81	46	23	13	711
	90°	14	25	38	89	105	124	128	90	62	35	18	10	541
North-east	30°	22	39	63	151	180	222	221	150	105	57	28	16	918
	45°	20	35	56	132	158	194	194	133	91	51	26	14	808
	60°	18	32	49	116	139	168	170	118	81	46	23	13	711
	90°	14	25	38	89	105	124	128	90	62	35	18	10	541
North	30°	20	34	54	137	173	217	214	142	90	49	26	15	857
	45°	19	32	47	101	143	184	180	115	66	45	24	14	710
	60°	17	29	44	79	109	143	139	90	59	41	22	13	575
	90°	14	23	34	64	81	99	100	70	48	33	18	10	433
Outdoor temperature ϑ_e, in °C		–1,3	0,6	4,1	9,5	12,9	15,7	18,0	18,3	14,4	9,1	4,7	1,3	8,9

Appendix E

Optimization results in Chapter 4

Table E.1: The Pareto optimal solutions of Case 1. Here x_1 and x_2 represent the variables of the external wall insulation materials for Phase 1 (year of construction : 1987), and Phase 2 (year of construction : 1993); x_3 to x_7 represent the variables of the roof insulation materials, windows, energy systems, PV systems, and lighting systems, respectively.

No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	Q_{pre} in kWh/a	C in kg/a	NPV in CNY
1	6	8	1	3	3	4	3	1.64E+05	4.67E+04	4.62E+06
2	6	8	1	3	0	4	3	1.33E+05	8.68E+03	4.82E+06
3	6	7	1	3	3	4	3	1.64E+05	4.69E+04	4.62E+06
4	6	7	1	3	0	4	3	1.33E+05	8.74E+03	4.82E+06
5	7	8	1	3	3	4	3	1.64E+05	4.65E+04	4.62E+06
6	6	10	1	3	0	4	3	1.32E+05	8.62E+03	4.84E+06
7	7	8	1	3	0	4	3	1.33E+05	8.64E+03	4.82E+06
8	7	7	1	3	3	4	3	1.64E+05	4.67E+04	4.62E+06
9	7	10	1	3	0	4	3	1.32E+05	8.58E+03	4.84E+06
10	7	12	1	3	0	4	3	1.34E+05	8.34E+03	4.85E+06
11	6	10	2	3	3	4	3	1.62E+05	4.61E+04	4.65E+06
12	6	11	2	3	0	4	3	1.30E+05	8.43E+03	4.87E+06
13	7	12	1	3	3	4	3	1.65E+05	4.61E+04	4.65E+06
14	6	12	2	3	3	4	3	1.64E+05	4.58E+04	4.66E+06
15	6	11	2	3	3	4	3	1.61E+05	4.59E+04	4.67E+06
16	6	10	2	3	0	4	3	1.31E+05	8.46E+03	4.85E+06
17	6	7	2	3	0	4	3	1.32E+05	8.57E+03	4.83E+06
18	7	7	2	3	3	4	3	1.63E+05	4.62E+04	4.64E+06
19	6	7	2	3	3	4	3	1.63E+05	4.64E+04	4.63E+06
20	7	12	2	3	3	4	3	1.64E+05	4.55E+04	4.66E+06
21	7	12	2	3	0	4	3	1.33E+05	8.17E+03	4.86E+06
22	7	7	2	3	0	4	3	1.32E+05	8.53E+03	4.83E+06
23	6	12	2	3	0	4	3	1.33E+05	8.21E+03	4.86E+06
24	7	10	2	3	0	4	3	1.31E+05	8.42E+03	4.86E+06

Table E.2: The Pareto optimal trade-offs between the initial investment cost I in CNY ×10^6, the annual primary energy consumption Q_{pre} in kWh/a ×10^5, and the annual CO_2 emissions C in kg/a ×10^4 in Case 2. The corresponding net present value N (in CNY ×10^6) is also calculated. Here each x_i represents the same variables with table E.1 on page 121

No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	I	Q_{pre}	C	N	No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	I	Q_{pre}	C	N
1	4	0	3	0	0	3	2	2.62	2.88	4.29	5.68	39	4	0	4	3	1	3	3	2.29	4.07	11.58	6.09
2	4	9	4	0	1	3	3	1.98	5.02	14.28	6.69	40	5	0	3	0	1	3	2	1.83	5.35	15.22	6.87
3	4	0	6	0	0	3	3	2.7	2.67	3.78	5.52	41	4	0	4	2	0	4	3	3.14	1.65	1.41	4.93
4	3	3	4	0	1	4	3	2.19	4.36	12.41	6.23	42	4	0	3	0	0	2	3	2.57	3.06	4.78	5.81
5	4	0	3	0	0	4	3	2.81	2.11	2.17	5.12	43	5	0	4	0	1	4	3	2.05	4.48	12.78	6.23
6	4	0	4	0	0	3	3	2.65	2.7	3.83	5.52	44	5	0	3	0	0	2	3	2.58	3.05	4.76	5.81
7	4	0	4	0	1	3	3	1.86	5.14	14.62	6.7	45	4	3	6	3	0	4	3	3.46	1.34	0.87	4.85
8	7	0	4	2	1	4	3	2.35	3.81	10.88	5.87	46	4	0	3	2	1	4	3	2.32	3.91	11.19	5.96
9	4	0	3	0	1	4	3	2.02	4.6	13.18	6.33	47	4	1	4	0	1	3	3	1.97	5.05	14.34	6.7
10	4	1	4	0	0	3	3	2.76	2.65	3.74	5.56	48	4	2	6	0	0	4	3	3.01	1.97	1.91	5.1
11	4	0	3	0	0	3	3	2.63	2.75	3.93	5.57	49	4	0	3	2	0	4	2	3.1	1.83	1.86	5.08
12	4	2	4	0	1	3	3	1.99	5.01	14.22	6.68	50	4	2	5	0	1	4	3	2.19	4.33	12.33	6.2
13	4	0	4	0	0	2	3	2.59	3.01	4.68	5.76	51	4	0	3	0	0	4	2	2.8	2.24	2.53	5.22
14	4	0	4	0	1	4	3	2.04	4.5	12.86	6.24	52	7	0	3	3	0	4	3	3.24	1.48	1.13	4.85
15	4	0	6	0	1	3	3	1.9	5.08	14.41	6.66	53	4	0	3	0	1	2	3	1.77	5.55	15.78	7.02
16	4	2	4	0	1	4	3	2.17	4.37	12.47	6.23	54	4	3	6	0	1	4	3	2.24	4.3	12.2	6.19
17	4	1	5	0	0	4	3	2.96	1.99	1.95	5.1	55	4	0	5	0	1	3	3	1.88	5.1	14.48	6.67
18	4	0	4	0	0	4	3	2.83	2.06	2.07	5.07	56	4	2	4	0	0	3	3	2.78	2.63	3.71	5.56
19	4	0	3	0	1	2	1	1.72	6.12	17.38	7.51	57	4	0	6	3	1	4	3	2.51	3.38	9.62	5.6
20	7	0	3	0	1	4	2	2	4.73	13.54	6.44	58	5	0	4	3	1	3	3	2.3	4.05	11.5	6.07
21	4	0	4	3	1	4	3	2.47	3.43	9.82	5.63	59	4	0	3	0	0	4	1	2.76	2.68	3.78	5.61
22	4	1	5	3	0	4	3	3.39	1.36	0.92	4.84	60	4	1	4	3	0	4	3	3.37	1.38	0.95	4.85
23	4	0	5	0	0	4	3	2.86	2.04	2.04	5.06	61	4	2	6	0	1	4	3	2.21	4.31	12.26	6.2
24	4	0	4	0	1	2	1	1.74	6.01	17.07	7.42	62	4	3	5	3	0	4	3	3.44	1.35	0.88	4.84
25	6	0	3	3	1	4	2	2.43	3.66	10.48	5.82	63	4	0	3	0	1	3	3	1.84	5.24	14.94	6.78
26	4	0	4	3	0	4	3	3.26	1.43	1.04	4.8	64	4	0	5	0	1	4	3	2.06	4.46	12.72	6.21
27	4	1	4	0	1	4	3	2.15	4.41	12.58	6.25	65	4	0	6	3	0	4	3	3.31	1.41	0.99	4.8
28	4	0	5	2	0	4	3	3.17	1.63	1.37	4.92	66	4	0	3	3	1	4	3	2.44	3.53	10.12	5.72
29	5	0	4	0	0	2	3	2.6	3	4.66	5.76	67	4	0	5	0	1	2	3	1.82	5.4	15.32	6.91
30	4	0	3	0	0	2	2	2.55	3.19	5.13	5.92	68	4	3	6	0	0	4	3	3.03	1.97	1.89	5.1
31	4	0	3	2	1	4	2	2.31	4.04	11.55	6.06	69	4	4	6	0	1	4	3	2.26	4.3	12.17	6.2
32	4	0	4	0	1	2	3	1.79	5.45	15.46	6.93	70	3	0	3	2	0	4	3	3.12	1.71	1.5	4.97
33	4	0	5	3	0	4	3	3.29	1.41	1	4.79	71	4	0	6	0	1	4	3	2.08	4.44	12.65	6.21
34	4	0	3	0	1	3	2	1.82	5.37	15.29	6.89	72	4	0	5	3	1	4	3	2.49	3.39	9.68	5.6
35	4	0	3	0	1	2	2	1.75	5.68	16.14	7.13	73	4	1	6	3	0	4	3	3.42	1.36	0.91	4.84
36	3	0	4	0	0	2	1	2.54	3.57	6.28	6.25	74	4	0	6	0	0	4	3	2.88	2.03	2.02	5.06
37	4	2	4	0	0	4	3	2.96	1.99	1.96	5.1	75	4	3	4	3	0	4	3	3.41	1.37	0.92	4.85
38	4	0	3	0	0	2	1	2.51	3.63	6.38	6.3												

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List of symbols and abbreviations

η primary energy factor

μ mean value of normal distribution

ω energy system efficiency

σ standard deviation of normal distribution

EF emission factor

I initial investment cost

Q_{pre} annual primary energy consumption

2D two dimensional

3D three dimensional

AHP analytical hierarchy process

BEMS building energy monitoring system

BIM building information modeling

BREEAM building research establishment environmental assessment methodology

CHP combined heat and power

CNY Chinese Yuan, 1 CNY = 0.16 USD = 0.12 EUR, currency exchange rates as of May, 2014

COP coefficient of performance

DGNB Deutsche Gesellschaft für Nachhaltiges Bauen, German sustainable building council

DHS district heating system

EEM energy efficiency measure

EnEV the German energy saving regulation

EPBD energy performance of buildings directive

EPS expanded polystyrene

eq. equivalent

ESCO energy service company, energy savings company

GHG greenhouse gas

GSHP ground source heat pump

GWP global warming potential

HoQ house of quality

HVAC heating, ventilation, and air conditioning

ICS integral collector storage

IDDS integrated design and delivery solution

IHL index of heat loss

IPCC intergovernmental panel on climate change

IPD integrated project delivery

kWp kilowatt peak

LCA life cycle assessment

LCCA life cycle cost assessment

LCIA life cycle impact assessment

LED light-emitting diode

LEED leadership in energy and environmental design

MAUT multiple-attribute utility theory

MAVT multiple-attribute value theory

MCA Monte Carlo analysis

MCDA multi-criteria decision analysis

MCDM multi-criteria decision making

MDO multidisciplinary design optimization

MOHURD the ministry of housing and urban-rural development (China)

MOO multi-objective optimization

NBS the national bureau of statistics (China)

NDRC the national development and reform commission (China)

No. number

NPV net present value

NSGA-II non-dominated sorting genetic algorithm-II

OECD organization for economic cooperation and development

PI performance indicator

PUR polyurethane foam

QFD quality function deployment

U-value heat-transfer coefficient

VBA Visual Basic for Applications

XPS extruded polystyrene