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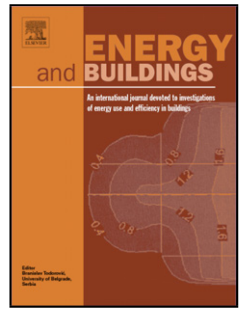

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PII: S0378-7788(14)00568-4
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2014.07.030
Reference: ENB 5180

To appear in: *ENB*

Received date: 9-5-2014
Revised date: 14-7-2014
Accepted date: 14-7-2014

Please cite this article as: Yunming Shao, Philipp Geyer, Werner Lang, Integrating requirement analysis and multi-objectiveoptimization for office building energy retrofit strategies, *Energy & Buildings* (2014), http://dx.doi.org/10.1016/j.enbuild.2014.07.030

Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies

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Abstract

The existing office building stock is a key target for energy retrofits to substantially reduce adverse impacts on the environment, human health, and the economy. Success of an energy retrofit project is tied with the assessment and selection of energy efficiency measures that can satisfy stakeholders' diverse, and often conflicting requirements. The current study establishes a model-based method to support design teams in making informed multi-criteria decisions for energy-efficiency solutions at the early design stage. The key feature of the hybrid framework is the integration of an analysis procedure carried out by a design team and a numerical procedure of optimization carried out by computer. Such an interaction is necessary as building design and retrofit requires many qualitative aspects that require human judgment.

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Preprint submitted to Energy and Buildings *July 11, 2014*

In contrast to previous approaches, this study provides a basis for embedding multi-objective optimization into the decision making on energy retrofit solutions, which considers the important role of stakeholders by carrying out the analysis procedure. An office building in Germany needing an energy retrofit serves as a case study to demonstrate the feasibility of the proposed model.

Keywords: Quality function deployment, energy retrofit, office buildings, interactive multi-objective optimization, decision support

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1. Introduction

Energy consumption of buildings accounts for almost 40% of global energy use. It becomes obvious that energy efficiency of buildings is a key component of reducing global energy use and climate harmful emissions. In general, the replacement rate of existing buildings by new buildings is only around 1.0-3.0% per annum [1]. Retrofitting the existing building stock for energy efficiency, on the other hand, has a significant effect on reducing the total energy demands. In Germany, the government is committed to reducing the primary energy demand of buildings by 80% by 2050, which requires increasing the rate of energy efficiency retrofits from the current 0.8% to 2.0% per year [2]. Therefore, there is a major need to develop not only energy-efficient but also economically efficient solutions made by informed multi-criteria decision making in building retrofit.

Compared with other building types, office buildings have one of the highest levels of energy consumption, which varies between 100 and 1000 kWh/m^2 per annum [3]. According to a recent report from Pike Research

[4], the market for energy efficiency retrofits in commercial buildings will nearly double by 2020, reaching $152 billion worldwide. In order to make buildings more energy-efficient, an extensive set of energy efficiency measures (EEMs) has been developed that contributes to minimizing the energy need of buildings, helps buildings to access renewable energy sources, and enables buildings to utilize fossil fuels as efficiently as possible. In order to retrofit a building with maximum sustainability, designers should consider effects of more and more technological options and there are more than 400 different EEMs that could be undertaken [5]. However, recent studies show that approximately 80% of all EEMs are selected without considering alternatives, which demonstrates that the decision to select a specific measure is highly intuitive [6]. 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 efficiency retrofit solution is a compromise between several stakeholders' requirements (e.g., investment costs, thermal comfort, energy saving). The stakeholder in this field include, but are not limited to, the owner, tenants, the design team consisting of designers and consultants from multiple disciplines, the maintenance and operational team, etc. They usually have fragmented expertise, and varying and, in most cases, conflicting requirements [7]. The question of how to find a consensus between the stakeholders by taking into account as many points of view as possible is quite challenging.

In order to avoid the highly intuitive selection of EEMs, various approaches have been proposed. In the field of energy efficiency retrofits, due to the high competing nature of the requirements, and the complexity as assisting and supporting tool, multi-objective optimization (MOO) method has gain more and more attention in dealing with the vast design space of EEMs. Kaklauskas et al. [8] developed a multivariate design method and multi-criteria analysis for building retrofits, determining the significance and the priorities of building retrofit alternatives, and selecting the most recommended variant. Flager et al. [9] applied the multidisciplinary design optimization (MDO) to a classroom building design for the optimization of structural and energy performance. Geyer [10] exploited the potential of MDO in building design for routine use by a systematic breakdown of architectural design into optimization models for the application of MDO. Juan et al. [11] developed a genetic algorithm-based decision support system for housing condition assessment that suggests optimal retrofit actions considering the trade-off between cost and quality.Chantrelle et al. [12] developed a multicriteria tool to evaluate the effect of renovation measures in terms of CO_2 emissions, investment cost, energy use and thermal comfort. Asadi et al. [13] proposed an analytical approach to examine the energy/cost saving trade-off for retrofit options in terms of the building facade and solar thermal system. In their later research [14], a simulation-based MOO approach is proposed to optimize the retrofit cost, energy savings, and thermal comfort of a residential building. Hamdy et al. [15] implemented a three-phase simulation-based MOO approach to minimize the environmental impacts and cost for a two-storey house and its HVAC system. Evins et al. [16] applied a design-of-experiments procedure to screen the significant variables to facilitate the optimization of carbon emissions and costs.

These areas of research have allowed many problems of buildings retrofit optimization to be addressed. However each building's energy retrofit is unique: it has its own characteristics and stakeholders which are generally different from others [17]. The common drawback of the existing approaches is that a requirement analysis is often neglected or not connected to the optimization tools without a structured interaction with the design team. Most of the studies focus on the exploration of mathematical optimization while the real problem of disintegrated design is not sufficiently mitigated. This paper argues that when exploring the design space, 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 inevitable.

Existing building stakeholders play an important role in determining the process of retrofits. They usually have varying and, in most cases, conflicting requirements, and fragmented expertise [1]. Several studies demonstrate that conflicting and opposing stakeholder requirements is one of the main barriers that limits the increase in the number of sustainably retrofitted buildings, and that a decision making framework to align the various requirements is necessary in order to develop an acceptable solution [18, 19, 20]. Requirement analysis techniques are needed to address the specific requirements on a building retrofit project. Alanne [21] presented a tree-structured criteria model in the context of multi-criteria decision-making (MCDM) to select building renovation actions. Loh et al. [22] designed an environmental assessment trade-off tool to support multi-stakeholder decision-making in the design process. An analytical hierarchy process (AHP) model is embedded in this tool to support trade-offs between different design criteria. Singhaputtangkul et al. [23] developed a knowledge-based decision support system to assess building envelopes. A quality function deployment (QFD) approach was applied to meet the needs and the requirements of the customers, which refer to all stakeholders of a project. Results from the case study showed that QFD has the potential to support early design decision-making processes.

The current study establishes a model to support decision-makers in making informed decisions on energy efficiency solutions at the early design stage. The new methodology aligns the existence of multiple and competing objectives and 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.

In the next section, the theory and methodology are presented with its application to a case study. Result analysis and discussion are made in Section 3. Finally, Section 4 summaries conclusions and discusses issues for future research.

2. Theory and methodology development

The methodology developed contains an analysis procedure to be carried out by design team and a numerical procedure of optimization carried out by computer (Figure 1). 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 properly 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.

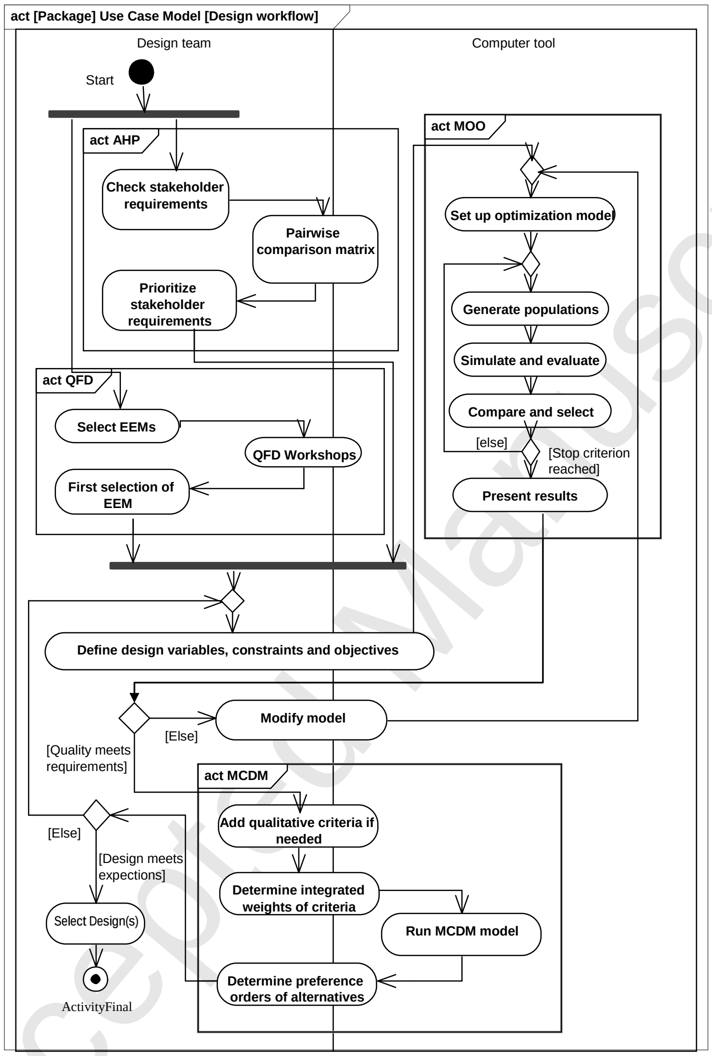

Figure 1: The activity diagram of the methodology serves to trace design process and optimization activities

2.1. Case building

The case study handles a non-air-conditioned, three-storey office building in Aachen, Germany. It was built in 1900, with a high primary annual energy demand up to 605 kWh/m^2 and a total energy demand of 540 kWh/m^2 per annum. The energy demand of the building exceeds roughly three times the reference values for old buildings stipulated in EnEV 2009 (the German Energy Saving Regulation). The basic information for this building is shown in Table 1.

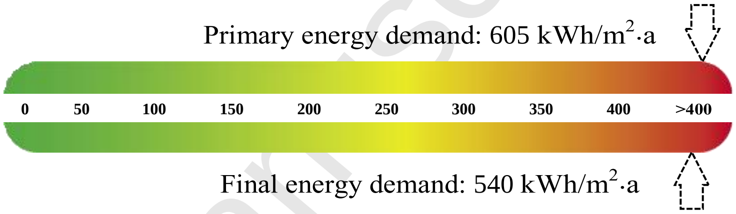

Figure 2: The office building in Aachen and its energy performance label

Table 1: Basic information on the case study, adapted from Meyer [24]

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^2K; Roof area: 168 m^2
	Exterior walls	Massive construction; Area: 327 m^2; U-value: 1.70 W/m^2K
	Basement	Unheated; Basement ceiling area: 117 m^2; U-value: 1.20 W/m^2K
	Windows	Wooden frame; Single-glazed; Window area: 54 m^2; U-value: 5.00 W/m^2K
	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

2.2. Design analysis

Successful energy efficiency retrofit solutions require both the achievement of stakeholder satisfaction and the optimization of the 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.

2.2.1. Stakeholders' requirements

It is obvious that one of the main requirements of an energy efficiency retrofit 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.

It is reported that inadequate consideration of stakeholders requirements in the early design stage is a major cause of poor performance of construction projects [23]. Note that 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.

In the early design phase, the requirements need to be quite general. These can be criteria like resource use and environmental loading. In order to support the design teams in identifying specific stakeholders requirements in the early design stage, a hierarchical structure of the requirements is established (Figure 3) containing an overview of different performance indicators that are used to quantify given performance aspects. This requirement tree could be used to help to define the criteria and constraints, and ensure that

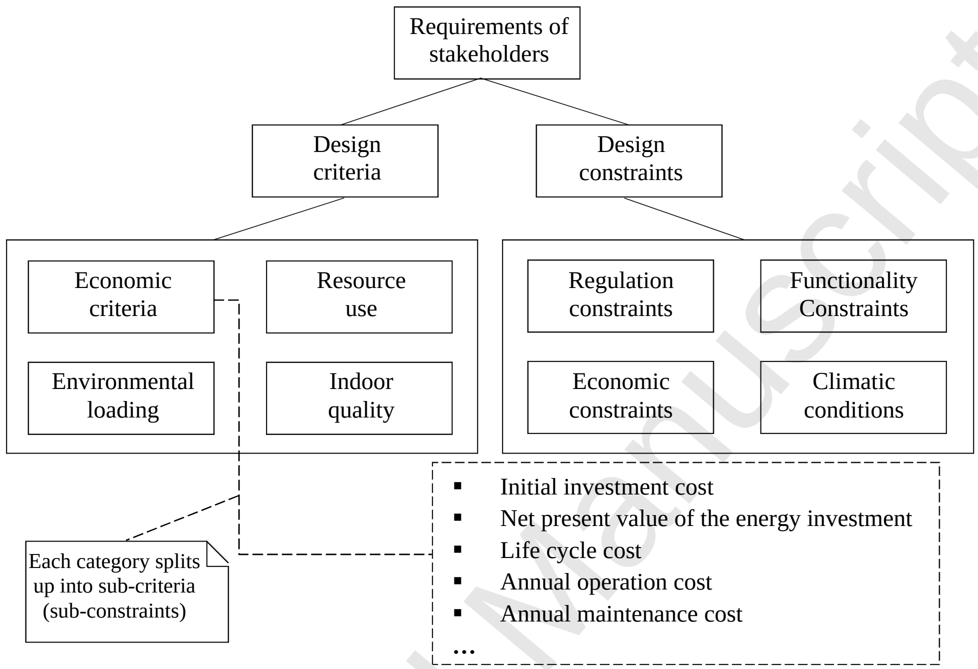

Figure 3: The hierarchical structure of the requirements of stakeholders

no important issues have been overlooked.

The requirements of stakeholders belong to two main categories: criteria and constraints. Criteria measure the matching objectives in design optimization problems. Generally, the following principles are followed to define the criteria used in selecting energy systems [25]: systemic, consistency, independency, measurability, and comparability. The category of design criteria consists of four main groups. The first group comprises 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 programming at the beginning. It is worth noting that climatic conditions must be integrated into the design process as the location of a building plays a large role in the building performance.

To define the design criteria and constraints, a pairwise comparison matrix between the requirements can be established. The analytical hierarchy process (AHP) is used in this study to obtain the weights based on the pairwise comparison of the criteria. Discussion of AHP is beyond the scope of this paper. As for design constraints, they are defined according to the actual conditions because constraints are compulsory in most cases. Typically, this is done through interactions and collaborations between the owner, the design team, and the facility users. The number of criteria depends on the case at hand. 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 should not be more than four.

For the case building, an AHP pairwise comparison matrix of the requirement checklist is conducted first to define the design criteria and constraints. Results show that the three selected criteria are the initial investment cost (R1), the annual operational energy consumption (R2), and the global-warming potential (GWP) effected by the annual CO_2 equivalent emissions and the embodied emissions (R3).

2.2.2. 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. The structure of EEMs can be 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.

When choosing potential options within the model, generally 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.

2.2.3. Development of the quality function deployment tool

Satisfying the needs and expectations of the customers is the utmost important goal for organizations in any industry. With this aim, lots of tools have been developed and adopted. Among these tools, QFD is regarded as highly effective, which is structured to systematically deal 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 "[26]. 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 and requirements "in building construction [27]. The whole process is driven by the main tool House of Quality (HoQ), whose name derives from its house-like appearance, using a matrix that relates customer needs to alternative options and compares them so that designers can concentrate on the most important and valuable characteristics. A basic HoQ contains 6 parts shown in Figure 4. Customer Requirements and Customer Importance Rating contain the list of voice of customers and its importance. 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.

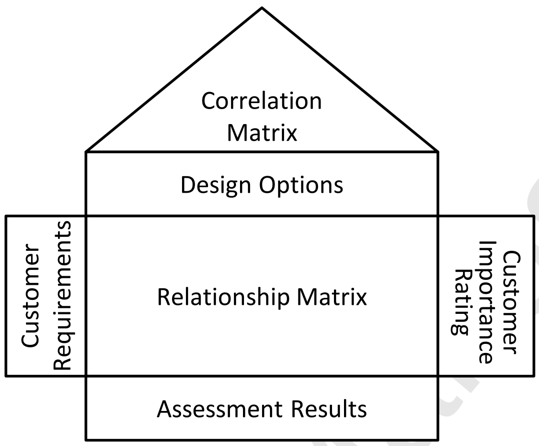

Figure 4: Basic House of Quality

In this study, a new QFD-based approach that supports decision-making on energy efficiency retrofits is developed (Figure 5). This tailored QFD table has five major parts, which are QA (stakeholder requirements), QB (EEMs), QC (relationship between stakeholder requirements and EEMs), QD (importance of stakeholder requirements), and QE (assessment results). The QA and QB are applied to identify relevant design criteria and constraints, and alternatives of EEMs, respectively. The QC contains the relationships between the design criteria (constraints) and the alternatives of EEMs. QD records the weight factors of the selected design criteria, whilst QE records the selected design variables of EEMs. The relationship matrix, QC, is defined by the design team based on the ontology of EEMs explained in Section 2.2.2.

In a retrofit project, a workshop which focuses on applying QFD can be 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 AHP should be applied to formulate the list and determine the critical items that should be included by collecting and analyzing data from stakeholders, while the constraints are derived from the project conditions. At this point, QA and QD are in place. The next step is to determine which EEMs are to be evaluated in relation to their impacts on each stakeholder requirement from Step 1 introduced in Section 2.2.2. Now that QA and QB of the matrix are in place, the third step is to put them together to determine their correlation values in QC. Each level of correlation is multiplied by the corresponding absolute weight of the design criterion. For example, a EEMs weak correlation of 2 is multiplied by a criterion's absolute weight of 5 to give a correlation value of 10. This calculation is carried for each correlation entered, and these correlation values are then totaled and converted to percentage weights. 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 should 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 should be considered as a dominating option. Finally, the sum of relative importance of each EEM that was just calculated in QC is taken and entered in QE. 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 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 comprise among stakeholders' analysis.

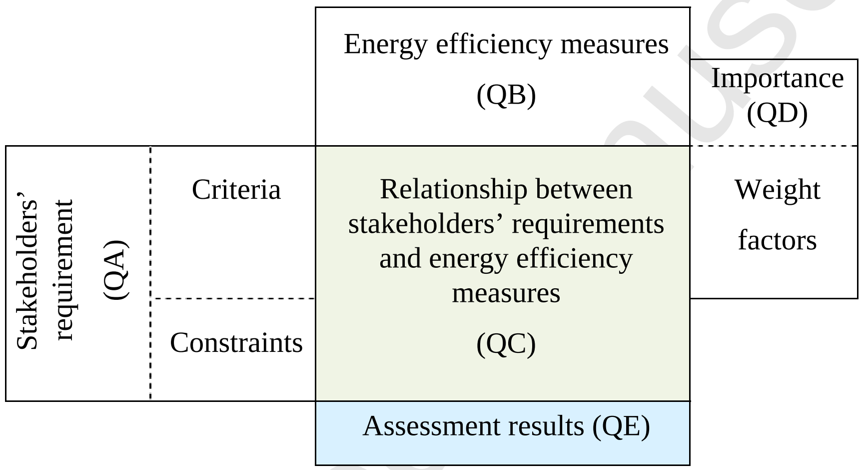

Figure 5: The planning of QFD for retrofit design

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 2). The weight 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 helps to identify the dominate priorities of certain EEMs.

Table 2: QFD analysis for the office building retrofit in Aachen, Germany

Criteria and Constraints	Direction of improvements	Insulate external walls	Insulate roofs / attics	Insulate floor	Renewable insulaton materials	Inprove building tightness	Glazing insulation	Advanced envelope technologies	Heating/cooling system	Building automation system	Photovoltaic (PV)	Weight factor	Weight factor %
Initial investment cost	Minmize	-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.

2.3. Multi-objective optimization

2.3.1. Principles of multi-objective optimization

In this study, the selection and integration of EEMs to formulate optimal solutions is regards as an MOO problem. In general, the mathematical expression of MOO problems can be shown as follows [28]:

$$\begin{aligned} &\text{minimize } f_i(x),\ i = 1,\dots,N_{obj}. \\ &\text{subject to } g_j(x) = 0,\ j = 1,\dots,Meq. \\ &\qquad\qquad h_k(x) \le 0,\ k = 1,\dots,Mineq. \end{aligned} \tag{1}$$

where f_i is the ith objective function, x is a design variable vector which represents a solution, N_{obj} is the number of objectives, Meq is the number of equality constraints, and $Mineq$ is the number of inequality constraints. Without loss of generality, all objective functions are of the minimization type - a maximization type objective can be converted to a minimization type by multiplying by negative one. The conventional optimization process requires a complete description of the objective function, f_i, and the constraints, g_j and h_k, the problem is then solved by selecting the best parameter vector.

Implementing the methods of optimization relies on 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. For such competing objectives, a set of optimal solutions is of interest. The reason for the interest in these optimal solutions is the fact that no solution can be considered to be better than any other with respect to all objective functions. These optimal solutions are known as Pareto optimal solutions (Figure 6).

In this situation, any two solutions x^1 and x^2 for a multi-objective optimization problem can have one of the two following possibilities: the first solution x^1 dominates or covers the other solution. In this case x^1 is called non-dominated (or dominated) solution or vice versa.

In a minimization problem, a solution x^1 covers or dominates x^2, if and only if, the following two conditions are satisfied:

$$\forall i \in \{1, \ldots, N_{obj}\} : f_i(x^1) \leq f_i(x^2) \tag{2}$$

$$\exists j \in \{1, \ldots, N_{obj}\} : f_j(x^1) < f_j(x^2) \tag{3}$$

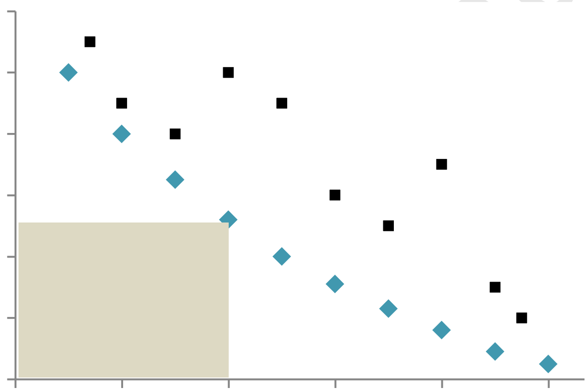

Figure 6: Pareto front example: diamond represents a Pareto solution for the minimization of two objectives

The solutions that are non-dominated within the entire search space constitute the Pareto optimal set. In this study, the method chosen is Non-dominated Sorting Genetic Algorithm-II (NSGA-II) [29], a multi-objective evolutionary algorithm to generate a set of Pareto optimal solutions. NSGA-II has been proven to be computationally efficient and reliable in building related optimization problems [12, 30, 31]. The MOO approach is combined with a building performance assessment model (Figure 7). An interactive cycle between the optimizer and the building performance assessment model is developed, where the optimizer will send a set of design variable values to the simulation model. The model is then executed with these values, the results, known as the objective values, 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 is able to generate a set of non-dominated retrofit solutions that can be evaluated by the design team with a higher level of information to choose one of the obtained solutions.

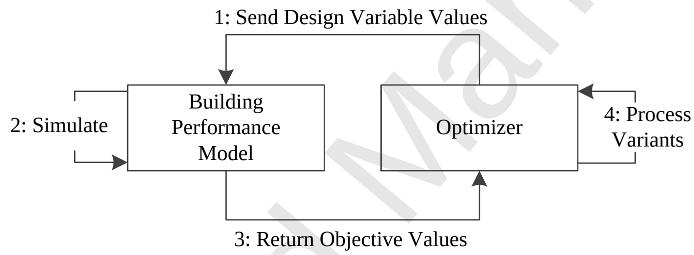

Figure 7: Optimization process

2.3.2. Design variables and design space

The retrofit solutions in this study concern combinations 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, cost). The entire design variables with their feasible regions comprise the design space that will be explored in the MOO model.

It is to be noted that the amount of design variables isn't necessarily equal to the amount of the EEMs selected form 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 there is no need to define it as a design variable for further evaluation. For example, option sustainable insulation materials 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. Table 3-8 present the six design variables and their properties. Sixteen insulation types for the external walls are described in Table 3. Fifteen insulation types for the roof are described in Table 4. Table 5 presents thirteen insulation types for the floor. Four types of windows are shown in Table 6, in which the embodied GWP is calculated based on the Beacon report [32]. Improving the building tightness is done by careful work, stricter control on the site, and additional work processes which create additional costs. It is assumed that the tightness $n_{50} = 4$ 1/h is the reference value with no additional costs. A smaller tightness value creating an additional cost (€/m^2) is shown in Table 7. Five types of heating systems are shown in Table 8. For the heating systems, the emission factor EF depends on not only the type of heating source, but also on the working processes of different heating systems.

The list of alternative EEMs shown in Table 3-8 is based on the LEGEP database [33] extracted by the authors and a short market survey. The GWP data were extracted from the Ecoinvent life-cycle database [34], and the chosen life cycle impact assessment (LCIA) method is IPCC 2007 (climate change) [35].

Table 3: Characteristics of external wall insulation materials

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

Table 4: Characteristics of sloped roof insulation materials

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

Table 5: Characteristics of basement ceiling insulation materials

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

Table 6: Characteristics of windows

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

Table 7: 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 8: 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

2.3.3. 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 should be defined to represent the criteria and constraints in the design optimization algorithm. For instance, if "minimize annual operational energy consumption" is defined as one of the objectives, the annual energy consumption indicator will be chosen to measure the objective function, and the building energy simulation module in the building performance assessment model will be 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 return the objective values to the optimizer for the next optimization process. Two types of relationships between different modules are defined (Figure 8). If both Module 1 and Module 2 receive the inputs separately, they are connected in parallel. If Module 2 needs the causation results from Module 1, then they are connected in series. In this case, if Module 2 is employed in the model, Module 1 will also be involved.

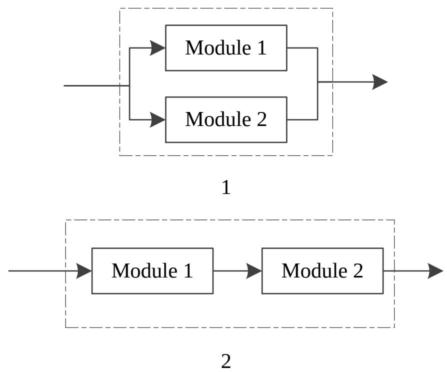

Figure 8: Module relationships in the building performance assessment model

As is analyzed before, three objective functions are identified in the case study. The initial investment cost is the summation of the investment cost for the selected EEMs and the additional cost for labor. It excludes the basic expenditures needed for a non-energy retrofit, assuming that the energy retrofit will be done additionally to a non-energy retrofit. The initial investment cost is calculated by the following equation:

$$R1 = \sum_{i=1}^{n} IC_i \tag{4}$$

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 be calculated in many ways. Since the case study is about an office building in Germany, the approach adopted is based on DIN V 18599, a holistic performance assessment method developed for German non-residential buildings. It provides a methodology for assessing the overall energy efficiency with all energy types required by the EU EPBD (heating, ventilation, cooling, lighting, and domestic hot water). The building energy simulation module was implemented in VBA for Microsoft Excel and it is used to calculate various energy performance indicators beside annual operational energy consumption. In general, the annual operational energy consumption can be expressed as:

$$
\begin{aligned}
R2 = & \sum (Q_{h,f,i} + Q_{h,aux,i}) + \sum (Q_{w,f,i} + Q_{w,aux,i}) \\
& + \sum (Q_{l,f,i} + Q_{l,aux,i}) + Q_{v,aux} + \sum (Q_{c,f,i} + Q_{c,aux,i})
\end{aligned} \tag{5}
$$

where $Q_{h,f,i}$ ($Q_{h,aux,i}$) is the delivered (auxiliary) energy supplied to the heating system by the energy carrier i and likewise, subscript with w, l, v, c means 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:

$$
R3 = \sum_{i=1}^{n} a_i GWP_i / L_i + Q \cdot EF / \omega \tag{6}
$$

where a_i is the gross amount of EEMs used in the building and $GWP_i(x)$ means the global warming potential of EEM i. L_i is the life time of EEM i; Q is the annual heating energy consumption; *EF* is the primary GWP factor of the heating device used in the solution, and ω 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 constrained by EnEV 2009. Indoor air quality and the climatic conditions such as annual temperature and solar radiation are also taken into account by defining the boundary conditions in the building energy simulation module properly.

2.3.4. Implicit constraints and architectural design

The situation of applying optimization on building differs from other fields of engineering because of building's peculiarities, the need to fit into their environment, and the strongly interact with users and society. Therefore, beside design criteria that are quantifiable, such as energy consumption, investment costs etc., qualitative criteria, e.g. appearance, spatial quality etc., play an important role in a retrofit project. These criteria require the assessment of designers and planners. There exist two different types of qualitative criteria that require different strategies:

1) Implicit criteria that can be quantified. Such criteria are geometrical dimensions or ratios of such dimensions that determine the appearance. These ratios can be quantified and included in a model by special modelling components describing these distances and ratios in an parametric spatial model. Figure 9 shows such elements developed in [36]. The use of utility functions allows the implementation of such criteria in the objective function expressing the preference for the individual design case.

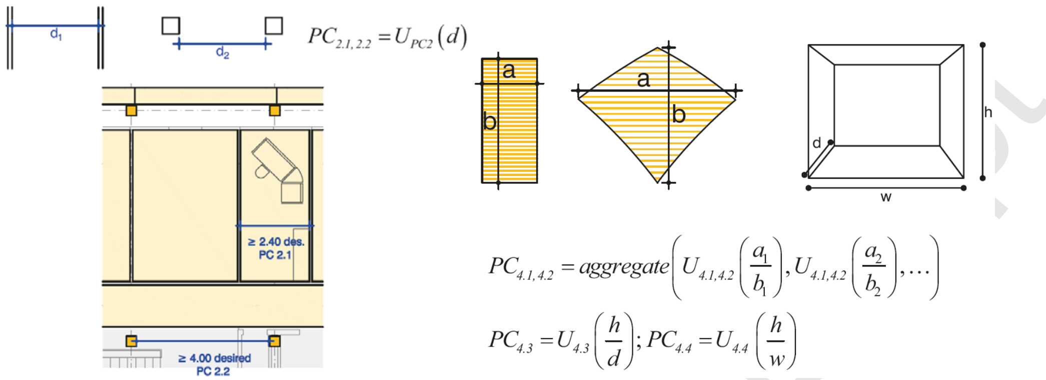

Figure 9: Special modeling components for quantifying qualitative criteria, an example

2) For the other criteria for that quantification in the described way is not possible, e.g., materials or composition, an interactive strategy allowing the designer to control them is required. The designers usually develop intentions regarding these criteria that to a large extend determine the identity of the design. Therefore, it is required to maintain these criteria constant during an optimization run. The structure of the components selected to describe the building and thus the optimization model and the variables selected for variation control these non-numeric aspects. As they form limitations that the optimization algorithm cannot change, we call them implicit constraints. For these implicit constraints that convey qualitative criteria of the design an interactive procedure, as shown in Figure 1, is required to allow designers to assess the qualities of the design and to adjust the model in an visual way. Currently ongoing research of Ritter et al. [37] tackles this need of an interactive visual setup of optimization models.

3. Optimization and discussion

3.1. 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 GWP is then carried out by means of the developed optimization model. As an evolutionary algorithm, NSGA-II performs an iterative and stochastic process in which an initial population of candidate solutions (called *individuals* or *chromosomes*) is made to evolve by means of genetic operators such as *crossover* and *mutation*. In the problem object of this paper, each chromosome codifies a possible solution to the retrofit problem in the form of an array of real values that identify, for each retrofit solution, its performance on the three objectives. For this purpose, 800 simulation runs are performed using a population size of 40 individuals and 20 generations. At each iteration (*generation*) the newly generated population is then evaluated by the simulation modules in terms of the three objectives. The non-dominated solutions are stored in an external archive, whose aims are to maintain the best solutions and to lead the algorithm towards the optimum Pareto-front.

3.2. Results and discussion

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 10). Table 9 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.

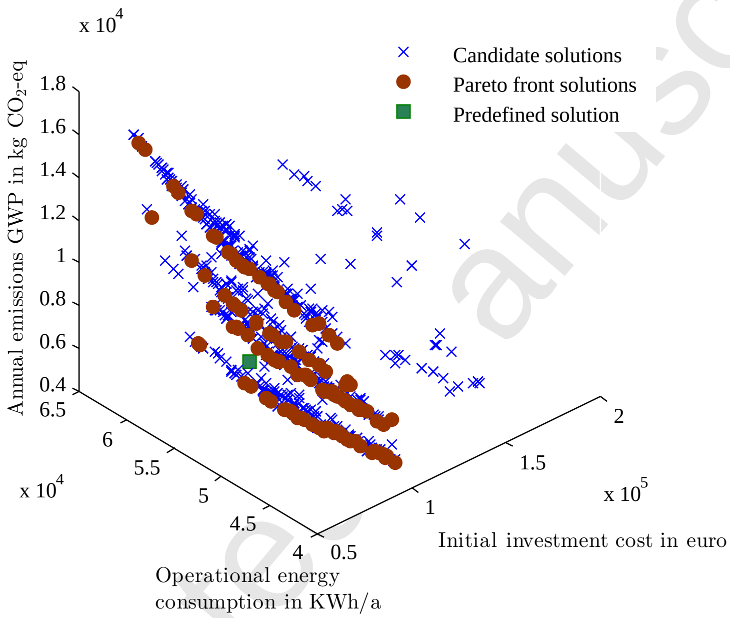

Figure 10: The Pareto optimal solutions and the candidate solutions of the case study

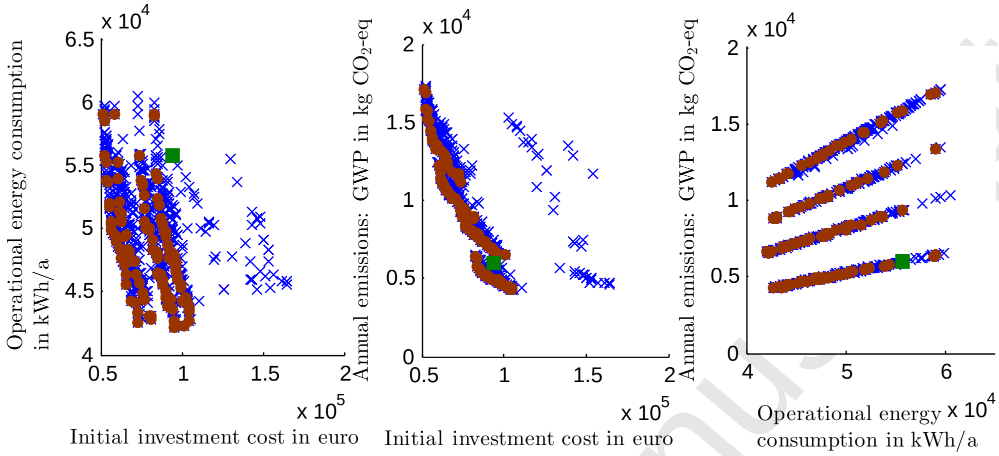

Figure 11: The two-dimensional projections of Pareto optimal solutions

To aid interpretation of the three-dimensional Pareto plot, the two-dimensional projections of the Pareto optimal solutions are shown in Figure 11. 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 10 and Figure 11). The corresponding values for the three objective functions are: initial investment cost €94000, annual operational energy 55700 kWh, and annual GWP 6020 kg CO_2-eq, respectively. From Table 9 it can be noticed that multiple optimal solutions (e.g., No. 5, No. 19, No. 33) have better performance than the predefined solution regarding all the criteria.

Table 9: Pareto optimal solution of the case study: x_i represents the six design variables described in Section 2.3.2, R1. R2, and R3 are 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	R1	R2	R3	No.	x_1	x_2	x_3	x_4	x_5	x_6	R1	R2	R3
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

In most of the cases, there are more than one, sometimes even hundreds of, optimal solutions. Whilst the benefit of MOO can only be realized if these optimal solutions can be analyzed in a way that aids the decision-making pocess of the selection of design solution(s). In order to access the qualities of the optimal solutions, other techniques (e.g., MCDM) have to be applied. In this way, the single solution or a set of alternative solutions that satisfy the stakeholders' preferences can be identified for further detailed design. 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 above mentioned three criteria and a list of normalized scores for each Pareto solution are presented in Table 10.

Table 10: Rank of the optimal solutions based on 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

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 €73200, the annual operational energy is 42600 kWh, and the annual GWP is 11200 kg CO_2-eq.

Compare with Rank 2, which is No.107, two scenarios differ in the types of insulations on the basement ceiling and the improvements of the air tightness. Figure 12 illustrates the comparison between energy efficiency measures applied in the scenario of No.76, regarding energy savings, GWP emission savings, and initial investment costs. A baseline model has been preliminary defined to describe the current state of the building. The ratios of annual operational energy saving and annual GWP emission saving 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. Thanks to the insulation of the external wall and sloped roof(i.e., x_1, x_2), significant energy savings can be achieved. In addition, the costs are much lower than installing highly insulation glazing (i.e., x_4). It is also found that with a relatively cheep low-temperature boiler for gas combustion, the emission saving of GWP is remarkable. The comparison shows the contributions of each EEM, but a holistic cost-effective reduction on energy use and GWP emission can not be achieved without the combination of the various design variables. The subsystems in buildings are highly interactive [38]. Different energy efficiency measures may have different impacts on associated building subsystems due to these interactions, requiring for a complex combination of energy efficiency technologies. This is also why solutions with various design variables instead of individual EEM are investigated.

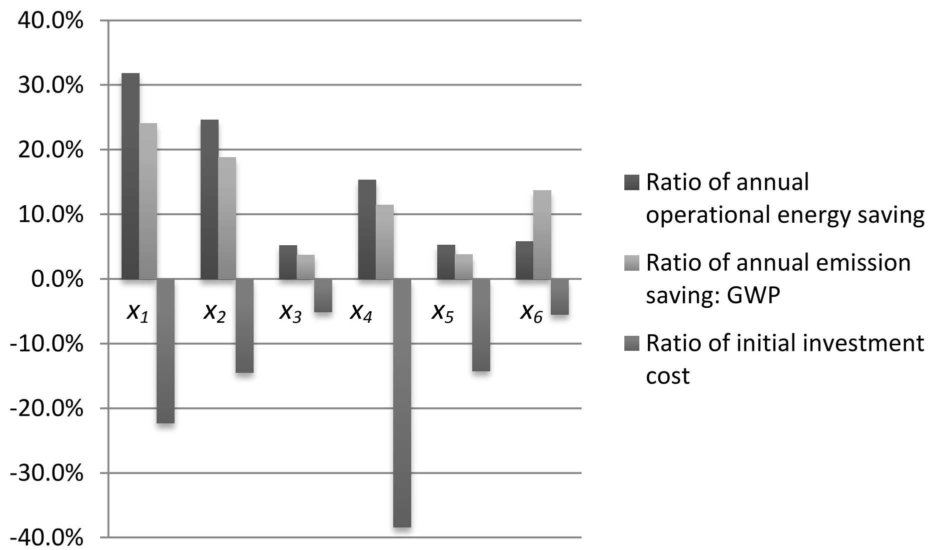

Figure 12: Energy savings, GWP emission savings, and initial investment costs. Comparison between energy efficiency measures applied in the scenario of No.76. x_i represents the six design variables described in Section 2.3.2

4. Conclusions

The improvement of energy efficiency in existing office buildings is a top priority worldwide. Nowadays an extensive set of EEMs 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. Both inadequate consideration of requirements and inadequate consideration of potential EEMs can cause significant adverse impacts to a project. In contrast to the other approaches mentioned, this study provides a basis for embedding MOO into the decision making process on energy efficiency retrofit solutions, which also considers the important role of the design team and develops a structured way for the interaction between the algorithm and the design team. By this means, building retrofits can be 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 at the early design stage. The new methodology aligns the existence of multiple and competing objectives, and the large number of potential energy efficiency measures. 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 bases in the 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 properly 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 modification of the optimization model with human reasoning.

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 unique assignment of weight factors of the conflicting objectives. To access the qualities of the optimal solutions, MCDM techniques are then applied. Since MCDM 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 on the selection of solutions. Note that decision-makers define the preference relations between pairs of alternatives with respect to every criterion, their preferences and insights still remain a significant influence on the final results of MCDM. Stakeholders' preferences should be analyzed again if more factors are to be considered and compared.

Acknowledgement

This research was supported by the China Scholarship Council funded by the State Scholarship Fund of the Education Ministry of the People's Republic of China (Scholarship No. 201206210033).

References

[1] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art, Energy and Buildings 55 (0) (2012) 889 – 902. doi:http://dx.doi.org/10.1016/j.enbuild.2012.08.018.

[2] K. Neuhoff, H. Amecke, K. Stelmakh, A. Rosenberg, A. Novikova, Meeting energy concept targets for residential retrofits in germany: Economic viability, financial support, and energy savings, CPI Brief, Climate Policy Initiative, Berlin (5 2011).
URL http://hdl.handle.net/10419/65901

[3] S. Burton, M. Sala, Energy efficient office refurbishment, Earthscan, 2001.

[4] N. Levin, W. Clint, Energy efficiency retrofits for commercial and public buildings, Pike research, Berlin (2012).
URL http://www.navigantresearch.com/

[5] D. R. Wulfinghoff, Energy efficiency manual, Vol. 3936, Energy Institute Press Maryland, 1999.

[6] P. de Wilde, M. van der Voorden, Providing computational support for the selection of energy saving building components, Energy and Buildings 36 (8) (2004) 749 – 758. doi:http://dx.doi.org/10.1016/j.enbuild.2004.01.003.

[7] Y. Shao, A systematic approach to energy efficiency improvements in buildings based on enterprise modeling method, in: Proceedings of SB13

Munich-Implementing Sustainability Changes, Munich, Germany, 2013, pp. 1283 – 1290.

[8] A. Kaklauskas, E. K. Zavadskas, S. Raslanas, Multivariant design and multiple criteria analysis of building refurbishments, Energy and Buildings 37 (4) (2005) 361 – 372. doi:http://dx.doi.org/10.1016/j.enbuild.2004.07.005.

[9] F. Flager, B. Welle, P. Bansal, G. Soremekun, J. Haymaker, Multidisciplinary process integration and design optimization of a classroom building, Journal of Information Technology in Construction 14 (2009) 595 – 612.

[10] P. Geyer, Component-oriented decomposition for multidisciplinary design optimization in building design, Advanced Engineering Informatics 23 (1) (2009) 12 – 31.

[11] Y.-K. Juan, J. H. Kim, K. Roper, D. Castro-Lacouture, Ga-based decision support system for housing condition assessment and refurbishment strategies, Automation in Construction 18 (4) (2009) 394 – 401. doi:http://dx.doi.org/10.1016/j.autcon.2008.10.006.

[12] F. P. Chantrelle, H. Lahmidi, W. Keilholz, M. E. Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Applied Energy 88 (4) (2011) 1386 – 1394. doi:http://dx.doi.org/10.1016/j.apenergy.2010.10.002.

[13] E. Asadi, M. G. da Silva, C. H. Antunes, L. Dias, Multi-objective optimization for building retrofit strategies: A model

and an application, Energy and Buildings 44 (0) (2012) 81 – 87. doi:http://dx.doi.org/10.1016/j.enbuild.2011.10.016.

[14] E. Asadi, M. G. da Silva, C. H. Antunes, L. Dias, A multi-objective optimization model for building retrofit strategies using trnsys simulations, genopt and matlab, Building and Environment 56 (0) (2012) 370 – 378. doi:http://dx.doi.org/10.1016/j.buildenv.2012.04.005.

[15] M. Hamdy, A. Hasan, K. Siren, Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings, Building and Environment 46 (1) (2011) 109 – 123. doi:http://dx.doi.org/10.1016/j.buildenv.2010.07.006.

[16] R. Evins, P. Pointer, R. Vaidyanathan, S. Burgess, A case study exploring regulated energy use in domestic buildings using design-of-experiments and multi-objective optimisation, Building and Environment 54 (0) (2012) 126 – 136. doi:http://dx.doi.org/10.1016/j.buildenv.2012.02.012.

[17] Y. Shao, Life-cycle management of high-performance and sustainable buildings based on enterprise modeling method, in: Green Design, Materials and Manufacturing Processes, Taylor & Francis Group, Lisbon, Portual, 2013, pp. 311 – 314.

[18] E. Rey, Office building retrofitting strategies: multicriteria approach of an architectural and technical issue, Energy and Buildings 36 (4) (2004) 367 – 372. doi:http://dx.doi.org/10.1016/j.enbuild.2004.01.015.

[19] A. Lapinski, M. Horman, D. Riley, Lean processes for sustainable project delivery, Journal of Construction Engineering and Management 132 (10) (2006) 1083–1091. doi:10.1061/(ASCE)0733-9364(2006)132:10(1083).

[20] L. Klotz, M. Horman, Counterfactual analysis of sustainable project delivery processes, Journal of Construction Engineering and Management 136 (5) (2010) 595–605. doi:10.1061/(ASCE)CO.1943-7862.0000148.

[21] K. Alanne, Selection of renovation actions using multi-criteria knapsack model, Automation in Construction 13 (3) (2004) 377 – 391. doi:http://dx.doi.org/10.1016/j.autcon.2003.12.004.

[22] E. Loh, T. Crosbie, N. Dawood, J. Dean, A framework and decision support system to increase building life cycle energy performance, Journal of Information Technology in Construction 15 (2010) 337 – 353.

[23] N. Singhaputtangkul, S. P. Low, A. L. Teo, B.-G. Hwang, Knowledge-based decision support system quality function deployment (KBDSS-QFD) tool for assessment of building envelopes, Automation in Construction 35 (0) (2013) 314 – 328. doi:http://dx.doi.org/10.1016/j.autcon.2013.05.017.

[24] L. M. Meyer, Entwicklung einer Sanierungsmatrix für historische Nichtwohngebäude am beispiel von Verwaltungsgebäuden, diploma thesis, Technical University of Dortmund (8 2010).

[25] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, J.-H. Zhao, Review on multi-criteria decision analysis aid in sustainable energy decision-making, Re-

newable and Sustainable Energy Reviews 13 (9) (2009) 2263 – 2278. doi:http://dx.doi.org/10.1016/j.rser.2009.06.021.

[26] Y. Akao, Development history of quality function deployment, The Customer Driven Approach to Quality Planning and Deployment (1994) 339 – 351.

[27] L. S. Pheng, L. Yeap, Quality function deployment in design/build projects, Journal of Architectural Engineering 7 (2) (2001) 30 – 39.

[28] M. Zeleny, J. L. Cochrane, Multiple criteria decision making, Vol. 25, McGraw-Hill New York, 1982.

[29] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multi-objective genetic algorithm: Nsga-ii, Evolutionary Computation, IEEE Transactions on 6 (2) (2002) 182 – 197.

[30] R. Evins, S. Joyce, P. Pointer, S. Sharma, R. Vaidyanathan, C. Williams, Multi-objective design optimisation : Getting more for less, Proceedings of the Institution of Civil Engineers - Civil Engineering 165 (5) (2012) 5–10. doi:10.1680/cien.11.00014.

[31] M. Hamdy, A. Hasan, K. Siren, A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the epbd-recast 2010, Energy and Buildings 56 (0) (2013) 189 – 203. doi:http://dx.doi.org/10.1016/j.enbuild.2012.08.023.

[32] D. Kellenberger, N. Perez, Lca-based windows calculator, Tech. rep., Pathway Ltd, Auckland (11 2008).

[33] Legep-software, a tool for integrated life-cycle analysis, http://www.legoe.de/.

[34] Ecoinvent database v2. 2, Swiss Center for life cycle assessment, Dübendorf, Switzerland.
URL http://www.ecoinvent.com

[35] S. Susan, Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, Vol. 4, Cambridge University Press, 2007.

[36] P. Geyer, Multidisciplinary grammars supporting design optimization of buildings, Research in Engineering Design 18 (4) (2008) 197–216. doi:10.1007/s00163-007-0038-6.

[37] F. Ritter, P. Geyer, A. Borrmann, The design space exploration assistance method: Constraints and objectives, in: Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, London, UK, 2013.

[38] S. Chidiac, E. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy 36 (8) (2011) 5037 – 5052, {PRES} 2010. doi:http://dx.doi.org/10.1016/j.energy.2011.05.050.