Master of Science in Engineering

Determining Retrofit Technologies for Building Energy Performance

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Abstract

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Worldwide the building sector is responsible for consuming more than 36% of the final global energy and produces 39% of carbon dioxide emissions. Accordingly, sustainable retrofit is an important method to achieve energy reduction and sustainable development. However, the lack of information on retrofit technologies and their benefits trigger stakeholder's opposition to retrofit actions. The Energy Performance Certificate tool can be used to overcome the knowledge gap and boost energy saving by strengthening its recommendation report with retrofit technologies for energy performance. Therefore, this paper attempts to determine the best retrofit technologies to be highlighted in the Energy Performance Certificate's recommendation report, by considering stakeholder's opinion. For this purpose, a model based on Quality Function Deployment has been developed. The model analyzes the data regarding stakeholder's expectations when deciding to retrofit, and the potential retrofit technologies used. In order to validate the applicability of the proposed model, a case study was conducted in Romania. The findings are expected to contribute to improving the quality of the Energy Performance Certificate, as reflecting stakeholder's opinion combined with sustainable concepts to achieve significant energy savings.

Keyword: Energy Efficiency; Energy Performance Certificate; Sustainable retrofit; Quality Function Deployment; Stakeholders

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Chapter 1. Introduction

This chapter briefly presents the retrofit project importance in achieving significant energy saving in the construction industry, and its relationship with the Energy Performance Certificate (EPC). Then, the chapter introduces barriers to driving retrofit processes and the research objectives that can help in shaping a better recommendation report of EPC. Additionally, the steps taken to achieve the goals are provided in the research process section.

1.1 Research Background

Building and construction industry has played a significant role in improving the population's quality of life and in meeting the demands and needs of the society. Despite the contribution of the construction industry, statistics show that it is highly unsustainable in terms of its impact on both the environment and economy. Globally, the construction sector is responsible for consuming more than 36% of the total energy produced and contributes to 39 % of global carbon dioxide emissions (UN Environment and IEA 2018; Alsanad 2015). Additionally, the International Energy Agency's Reference Technology Scenario shows that final energy demand in the global building sector will increase up to 30 % by 2060 if there is no more ambitious effort to address low carbon and energy-efficient solutions for buildings and construction industry (IEA 2017). With this, the International Energy Agency has released 25 energy efficiency policy recommendations to reduce energy consumption and carbon dioxide emissions. If the recommendations are enforced worldwide, 7.6 gigatonnes of carbon dioxide emissions could be saved annually by 2030. (Park et al. 2015). Herewith, in the last few decades, numerous countries have introduced energy performance certification as a key policy instrument that can help the government to reduce energy consumption in the building sector (IEA 2010; Park et al. 2015). This certification process helps the consumers in achieving a specified level of energy performance in their building.

The energy efficiency retrofitting for existing buildings is considered as an excellent method to achieve the targets of energy reduction and sustainable development. Although retrofit projects have many benefits, it is still a complicated area to be accessed and is considered as “one of the riskiest, complex, and uncertain within the construction industry” (Ali, Rahmat, & Hassan, 2008; Liang, Shen, & Guo, 2015). An energy efficient retrofit project is more complex and riskier than a general retrofit project because of the lack of information about the existing building (Ali et al., 2008; Liang et al., 2015), complicate financial sharing (Liang et al., 2015), and increased stakeholder interactions (Klotz & Horman, 2009; Liang et al., 2015). Explaining the lack of information problem in detail it is important because the owners and tenants have a significant interest in the building, its operation, and the outcome of the retrofit (Menassa & Baer, 2014). Moreover, a decision on whether a building should undergo sustainable retrofitting needs to be agreed on by the building owner (Klotz & Horman, 2009). Therefore, the owner and tenant should have the essential knowledge about sustainable retrofit and technical methods in order to decide to retrofit and lead an excellent performance improvement from the retrofits (Anagnostopoulos, Arcipowska, & Mariottini, 2015).

However, many studies show that owners and tenants have a lack of knowledge about when, how and why a building should be sustainably retrofitted (Bernstein et al., n.d.; Lapinski, Horman, and Riley 2006; Menassa and Baer 2014).

Additionally, stakeholders can have a different opinion about the retrofit process because their needs and expectations are changed along with their own experiences and viewpoints (Chun & Cho, 2018). For example, the owner may be motivated to sustainable retrofit to reduce the total energy costs and increase the return of the investment. On the other hand, the tenant can be interested in improving comfort, health, and productivity. Hence, aligning stakeholders demands and involving them in the process of the retrofit is a major objective to be addressed in order to achieve effective energy savings from the retrofit process. With this, policymakers are assigned to develop policies and directives addressing the issue of stakeholder's opposition to carry on retrofit activities.

Since the lack of information about the retrofit process is being an issue, Energy Performance Certificates (EPC) are considered to provide solutions to it (Anagnostopoulos, Arcipowska, and Mariottini 2015). The objectives of EPCs are to provide significant information to the owner and act as a catalyst to transform the market mechanism sustainably. To achieve this purpose, they suggest a recommendation report to encourage stakeholders who have the willingness to retrofit. The recommendation report can be divided into two categories: standard and tailor-made. The standard recommendations are more generic form and provide the general potential of building components. In this case, the building owner might not be motivated enough to carry out retrofit implementation. On the other hand, the tailor-made EPC recommendations give to the individual building owner proper support in what needs to be done for the energy efficiency of the building. Besides, they engage the stakeholders to deal more intensively with energy issues (Geissler and Altmann 2015) and are an essential support tool for building owners, facilitating the decision-making about renovation methods (Gonzalez Caceres, 2018; Petran, Geissler, & Vlachos, 2017).

1.2 Problem statement

Many studies ,including the one by the Buildings Performance Institute Europe (BPIE) (2014), have emphasized that the EPCs have a positive impact on consumers including homeowners and tenants by offering essential information about energy performance (Arcipowska et al. 2014; Comerford, Lange, and Moro 2018; van Middelkoop, Vringer, and Visser 2017). On the other hands, a study by Individual Building Renovation Roadmaps (iBRoad) (2018) about the current use of EPCs in its eight partner countries shows that the recommendations included are often considered as being too generic and that EPCs play a minor role when owners decide to retrofit. Some of its findings point that EPCs recommendation reports are not documented by experts or do not suggest system optimization methodologies and scenarios in Belgium, Germany, and Romania. The provided recommendations need to be explained or interpret to the owner by the expert. Therefore, it is necessary for improvement of the existent recommendation report.

Concerted Action-Energy Performance of Building Joint (2015) also states that there is a lack of clear definitions of tailor-made and standard EPCs, as well as of what type of information should be included in the report. Also, that more detailed retrofitting advice is required to support stakeholders in the decision-making process for retrofitting than what EPCs currently provide.

1.3 Research Objectives

Considering the literature containing negative opinions, the EPCs cannot reach their full potential in driving energy savings and to minimize the information deficit that the stakeholders have when retrofitting. Therefore, the objective of this research is to develop a model which evaluates the impact of different retrofit technologies on stakeholder's expectations for retrofit actions. The model aims to set the priority of retrofit technologies to support the stakeholder's decision-making to retrofit and to develop a process to integrate the findings with the existing EPC's recommendation. Through the conduction of surveys and analyses, the ranking of the retrofit technologies and how the stakeholder's demands affect the hierarchy of those methods will be determined.These factors will be determined relative to stakeholders' perceptions concerning the economic, social and environmental concept. Moreover, the retrofit technologies will be classified into four main technical categories of sustainable retrofit:(1) mechanical, (2) plumbing, (3) electrical and (4) building envelope system, respectively.

Furthermore, this research conducts a case study by using the proposed model based on Quality Function Development technique. As a result of the case study, the relationship between Energy Performance Certificates and the sustainable retrofit process will be identified. It will also help to comprehend the stakeholders' motivation to retrofit sustainable and technical methods with the potential to fulfill stakeholders needs. In this context, this research intends to provide valuable information about the stakeholders' drivers to retrofit and technical methods which can satisfy those drivers.

1.4 Research Process

This research process follows a three-step process as can be shown in the diagram presented in Figure 1.1. The first step starts with a Preliminary Study which has the role of helping in understanding the sustainable building retrofit process and factors which help in its success. Also, it introduces the Energy Performance Certificate type and its recommendation report which helps in understanding the current situation of the tool. Moreover, the preliminary study would help to narrow the objectives of this research, providing the information required to help in encouraging stakeholders in the decision making of retrofit projects. This step has also a brief introduction of the Quality Function Deployment technique and its application in the construction industry, which will help in understanding the tool used to achieve the scope of this study.

The second part presents the steps made in order to develop the model that will help to analyze stakeholders requirements and indicate which retrofit technology should be introduced first in the EPC's recommendation report.

The third step includes an application of the model with a study case, followed by discussions and conclusions.

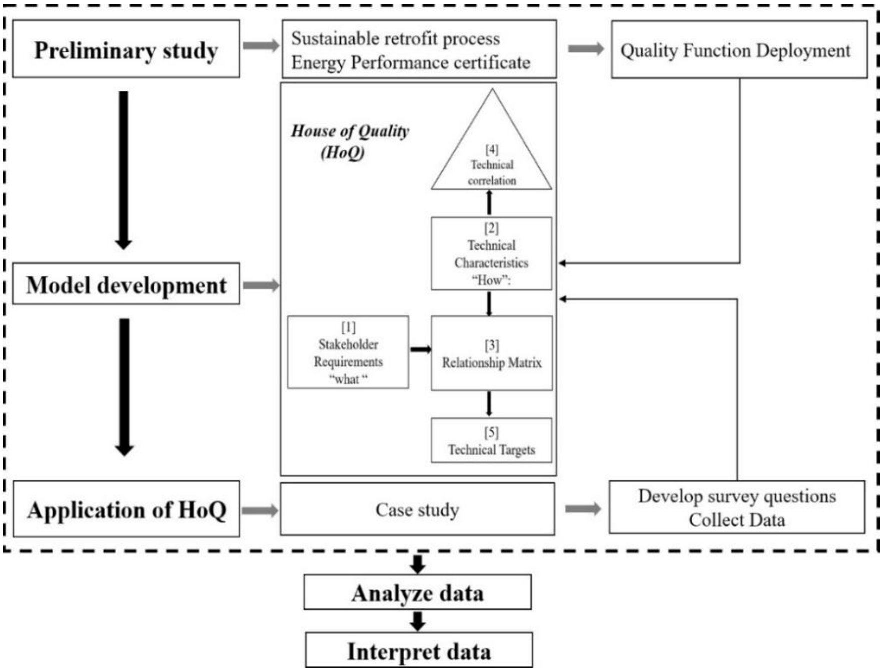


Figure 1.1 Research process

Chapter 2. Preliminary study

In order to find the intended retrofit technologies to be highlighted in the original EPC report of recommendation, it is necessary to gain knowledge about the retrofit projects and EPCs. Therefore, this chapter introduces information about sustainable building retrofit, its importance and critical factors to its implementation. Moreover, it shows the current situation of Energy Performance Certificate and the potential of the recommendation report to boost energy savings. Also briefly introduces the quality technique, Quality Function Deployment, which will be used to evaluate the variables integrated in the process of finding the primary retrofit technologies.

2.1 Sustainable Building Retrofit

The sustainable retrofit process was defined as the "upgrade" of components or elements of a building with the scope of improving the building's environmental performance (Tan et al. 2018). The "retrofit" also refers to other terms in literature such as refurbishment, rehabilitation, renovation, improvements, and repairs on existing buildings (Liang, Shen, and Guo 2015). Moreover, sustainable retrofit is defined as "any kind of upgrading of the building fabric, systems or controls to improve the energy performance of the property" (P. Brown, Swan, and Chahal 2014). In more detail the retrofit process was defined by the U.S. Green Building Council as " an upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality,and noise - all done in a way that it is financially beneficial to the owner" (Tan et al. 2018). From these definitions, it can be observed that a sustainable retrofit process focuses on improving the energy performance of a building.

In both developed and developing countries, extensive studies on sustainable retrofit have been carried out from various aspects. Examples of these include studies of stakeholders attitude of sustainable retrofit (Menassa and Baer 2014; Liang, Peng, and Shen 2016; Thuvander et al. 2012), retrofit technologies (e.g., mechanical and electrical system refurbishment solution, envelope renovation technologies and plumbing system retrofit solution) (Ruparathna, Hewage, and Sadiq 2016; Ascione et al. 2019; Francisco Pinto and Carrilho da Graça 2018) and studies about policies (Wilson, Crane, and Chryssochoidis 2015; Ebrahimigharehbaghi et al. 2019; D'Agostino, Zangheri, and Castellazzi 2017).

Previous studies show that sustainable retrofit actions provide not just excellent opportunities to reduce energy consumption in buildings but also implementations of sustainability in other ways such as environmental protection, intellectual resources use, and occupants' healthcare (Xu, Chan, and Qian 2011). Moreover, sustainable retrofit improves the performance and prevents the early onset obsolescence increasing the life span of a building (Menassa and Baer 2014). Santamouris and Dascalaki (2002) noted on the energy saving potential of selected retrofit options for five office building types in four different European zones using computer simulations. The selected retrofit options were intervention on the building envelope, HVAC, combination of passive components for cooling and heating, and the artificial lighting systems. Zheng and Lai (2018) conducted a study case on commercial building and underscore the importance of considering the degradation factor in the pursuit of rigorous environmental and economic evaluations of energy retrofits. Rey et al. (Rey 2004) created a multiple criteria methodology for evaluating office building retrofit strategies. This methodology considers environmental, economic and social criteria at the same time.

Parker and Bin (2012) compared the original and retrofit ecological footprint of a two-story single detached brick house build in 1910. The used retrofit technologies were insulation of the roof, walls, foundation and basement floor, replacement of the windows and doors, energy efficient appliances and renewable energy. The results showed that the environmental upfront cost of the retrofits would be offset within two years. Stovall (Stovall et al. 2007) conducted several experiments on typical houses in multiple locations, to examine wall retrofit options. The study used wall retrofit technologies and methods for replacement of windows, and it was found that external insulative sheathing is especially useful in reducing the heat transfer through walls. In most of the locations, the annual utility cost savings were 10%. Persily and Nabinger (2011) made a retrofit study in an unoccupied manufactured house, build in 2002, to examine the impacts of air-tightening on ventilation rates and energy consumption. For the study, house wrap over the exterior walls was installed and the leakages sites in the living space floor and the air distribution system were sealed. The results showed that the retrofit methods reduced the building envelope's leakage by 18% and duct leakage by 80%. As a total result, 10% of energy savings were obtained.

2.2 Critical factors in the success of a sustainable retrofit process

Considering the energy performance improvement, previous studies about the retrofit processes pointed out two critical factors for successful sustainable retrofit activities. These factors are lack of information about the retrofit process and the selection of retrofit technologies to be used in the retrofit process.

Studies have shown that lack of information about the process and implications of sustainable retrofitting is one of the main obstacles to sustainable retrofit along with financial barriers (Gohardani, Klintberg, and Björk 2015; Murphy 2014; Baek and Park 2012). Sustainable retrofit projects involve complex processes usually unfamiliar to stakeholders. The stakeholders can be defined as people who have a significant interest in the building, its operation, and the outcome of the retrofit; the owner and the tenant (Menassa and Baer 2014). Moreover, the building's owner generally becomes a subject who decides whether a building should be sustainably retrofitted. Therefore, owners should have the essential knowledge about sustainable retrofit and technical methods to have an excellent retrofitting performance result (Anagnostopoulos, Arcipowska, and Mariottini 2015). With this, the Energy Performance Certificate can be seen as a reaction to the "information deficit" referring to building owner's lack of knowledge of actions to carry out in order to enhance the energy performance of their building (Gonzalez Caceres 2018; Hoicka, Parker, and Andrey 2014).

Another critical factor that affects the success of sustainable retrofit is the selection of the retrofit technologies applied in the retrofit process. D'Agostino et al. (2017) stated that the benefits of sustainable retrofit could be achieved by applying a proper combination of efficient retrofit technologies is applied. Also, Tryson et al. (2016) considered that availed technologies are the basement to improve building performance. Two aspects are deducted from these statements: technical intervention is the primary measure in improving the building's performance while innovation and implementation of new advanced technologies control the economic growth, stakeholder satisfaction and environment protection (Tan et al. 2018). Therefore, access to retrofit technologies and its advancement should be considered as significant factors affecting sustainable retrofit.

2.3 Energy Performance Certificates

Building energy certification includes programmes and policies that evaluate the performance of a building and its energy service systems. Certification may focus on rating operational energy use or the expected energy use of the building. It can be voluntary or mandatory for all or parts of the buildings sector (UN Environment & IEA, 2018). According to the International Energy Agency's 2018 Global Status report 85 countries have adopted building certification programmes. Even though the use of certification programmes is growing, there is still a lack of large-scale adoption of full mandatory certification programmes outside the European Union, which means that tracking of building energy performance over time and subsequent disclosure are still limited.

In the European Union, the Energy Performance Certificate (EPC) was implemented as a requirement by the Energy Performance of Building Directive 2002 (recast 2010) with most Member State requiring the EPC by 2008. Its goal is, first to reduce the carbon dioxide emissions by increasing the investment in energy efficiency and second to serve as an information tool for stakeholders (Anagnostopoulos et al., 2015). The Certificate represents a report on the calculated energy performance of a specific building with a rating scale between A and G, with A being the most energy-efficient environment-friendly and G the least energy efficient environment-friendly. In the United States of America, similar efforts to European's EPC were initiated in 2009 through the ASHRAE Building Energy Quotient (Building EQ), a program to drive the reduction of the energy use in commercial buildings by indicating the energy performance of buildings in an effective way. The ASHRAE's program (Www.ashrae.org, n.d.) provides a method to rate buildings energy performance both for designed and operating stages (Hotel, 2011). Besides the EU and the U.S.A, building energy efficiency rating systems are implemented in Asia, as well. For example, South Korea adopted a similar system to the EPCs from EU, named as Building Energy Efficiency Certification, to systematically control the energy consumption and GHG emissions of its existing buildings.

A comparison of these three certification types can be seen in Table 1. As shown in the table, the Europe Union's certificates can be used for all building, whereas in the case of U.S.A and South Korea, the applicable types of the building are limited and there is no compulsory program for post-certification management, the management of energy efficiency in buildings is practically non-existent, compared to Europe. Also, ways that can improve the energy efficiency of the building are implemented just in Europe and the U.S.A, with the mention that U.S.A's certificate focusing on commercial buildings does not boost energy efficiency for residential buildings. Among the various energy performance certificates, this research continues the discussion based on the most enforced and influential one, the European EPC.

Table 2.1 Comparison of the Energy Performance Certificates

	Europe	**U.S. A**	**South Korea**
Classification	-EPBD's Energy Performance Certificate	-Building EQ	-Building Energy -Efficiency Certification System
Regulation	-Mandatory	-Voluntary	-Voluntary
Target	-All Building types	-Commercial Buildings	-Apartments and commercial buildings
Range for evaluation	Energy performance	-Energy performance evaluation and recommendations to improve energy efficiency	-Energy reduction rate
Evaluation items	-Building energy efficiency -Ways that can improve the efficiency of housing	-Building energy efficiency -Means to improve the building's energy performance	-Analysis of "primary energy requirements per annual unit area," such as air conditioning, hot water supply, lighting, ventilation

2.4 Previous research on the EPC's Recommendation Report

In 2010 the Energy Performance of Building Directive strengthened the EU EPCs by introducing a compulsory recommendation report which contains a list of methods to be taken to boost energy savings. This recommendation report is considered especially crucial for improving the energy efficiency of existing buildings (Geissler & Geissler, 2015). Not only it can provide an overview on the improvement potential of the thermal envelope of the building (e.g., external walls and windows) but also can take into consideration how to optimize or replace the energy performance of the mechanical systems (e.g heating, cooling), plumbing system (hot water system) and electrical system (lighting fixture).

As seen in Figure 2.1 the EPC recommendation report can be issued by an Accredited Energy Auditor (AEA) after he/she inspects the property. AEA can determine what type of report will issue, either "standard" or "tailor-made." The standard report shows the general improvement potential of the upgrading or replacement of heating, air conditioning, and hot water systems for energy efficiency or thermal performance (e.g., U-value) of the roof, floor, external walls and windows according to the building type and age (Geissler and Altmann 2015). This information, however, does not have a significant potential to motivate enough the owner to carry out retrofit actions. On the other hand, the tailor-made EPC recommendation report not only indicates the energy efficiency potential of the building but also suggest specific renovation methods, such as the fitting of heating and domestic hot water system, the quality of the windows or the thickness and quality of the insulation, according to conditions of a specific building. If it provides appropriate information, the tailor-made recommendation can provide better support to the owner's decision-making in what needs to be done about the energy of the building. However, from previous research, it can be found that most of the EU Member States do not require this level of precision in practice, the Korean Energy Certificate has no recommendation report, and the U.S's Building EQ provides actionable recommendations about estimated costs and payback information to be used to improve building energy performance, but it is not applicable for residential buildings.

Moreover, a study about stakeholder's attitude conducted in 10 EU countries from 2007 to 2011, on domestic EPCs suggested that 80% of respondent were aware of EPCs, and 60% found EPCs easy to understand. However, the recommendations were considered less easy to understand, and only 17% of owners in the U.K recalled that the EPC had recommendations included (Better Buildings Partnership, 2018). Another study made by Concerted Action-Energy Performance of Building Joint et al. (Geissler & Geissler, 2015) and Petran et al. (2017) showed that in many countries, the EPC presents only a general recommendation about the renovation. The information is not sufficiently detailed for decision-making on renovation projects. Specific retrofit methods plus financial incentives and payback periods are missing.

Reports by the Evaluation of the Directive 2010/31/EU indicate that the recommendation report is affected by lack of information on how to plan and implement improvements of energy efficiency in building over time or the absence of an appropriate retrofit list of actions (Gonzalez Caceres 2018). On this aspect, the report concluded that policies regarding recommendations should explore new approaches to remove these barriers. For example, some countries (e.g., Austria) are developing tools and procedures to produce on-site tailor-made recommendation packages which can show clear benefits of retrofit (Geissler and Altmann 2015). Moreover, the usefulness of the EPCs could be increased through a better-documented recommendation report containing the information about well-organized retrofit processes, since owners and tenants tend to undertake retrofit actions when supporting information is given (Anagnostopoulos, Arcipowska, and Mariottini 2015; iBRoad project 2018; Gonzalez Caceres 2018). Therefore, by using the proposed model, the recommendation report can be better documented in the direction of effective energy savings by highlighting the primary retrofit technologies to be applied. Also, by considering stakeholder's opinion into the developing process of the model, the stakeholder can participate actively in the process of selecting the retrofit technologies. As a result, the owner will be able to obtain better incentives and be motivated to retrofit.

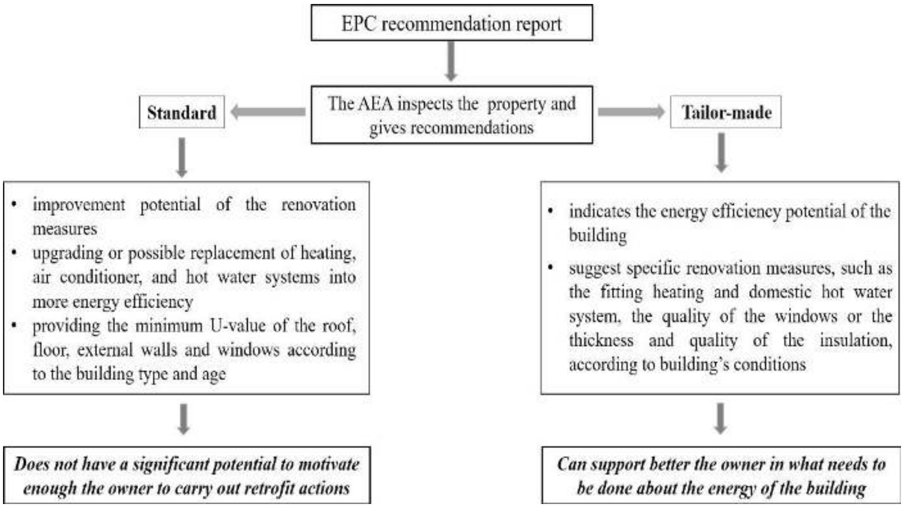


Figure 2. 1 Types of EPC recommendation report and their outcome

2.5 Quality Function Deployment

2.5.1 The Concept of Quality Function Deployment

Quality Function Deployment is a customer-driven methodology in which customer's needs are systematically translated into product specifications. (Chun and Cho 2015, 2018; Oh, Cho, and Kim 2017). More specific it is "a method for structured product planning and development that enables a development team to specify the customer's wants and needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs." (Delgado-Hernandez, Bampton, and Aspinwall 2007).

The QFD was first used in the Kobe shipyards during the 1960s by Mitsubishi Heavy Industries for ships which needed early design freezes, and in the 1970s it was used by Toyota to investigate rust prevention in vehicles. The methodology was developed in a four-phase quality technique (house of quality, part deployment, process planning, and operations planning) by Clausing, carrying the opinion of the customer from the high-level system to monitoring the product in production (Cudney and Gillis 2017; Wood et al. 2016). The first phase, the house of quality (HoQ) is seen as a major tool which offers a way to match the design of the product with the opinion of the customer or customer requirements (Cudney and Gillis 2017). As shown in Figure 3.1 HoQ contains rooms, each of which holds information specific to achieve targets of the research. The room (A) represents a list of customer requirements. It contains customer needs or their expectations for a particular task. Room (C) refers to a list of technical characteristics that can have an impact on one or more of the customer demands. The room (E) maintains an interrelationship matrix between technical characteristics and the fourth room (D) registers a relationship matrix between the customer requirements and technical characteristics. The rooms (B) and (F) contain calculation algorithms for prioritizing the customer's demands and technical characteristics (Coble and Jr 1999; Singhaputtangkul et al. 2013). The order presented by the letters A to F is generally followed during the process of HoQ.

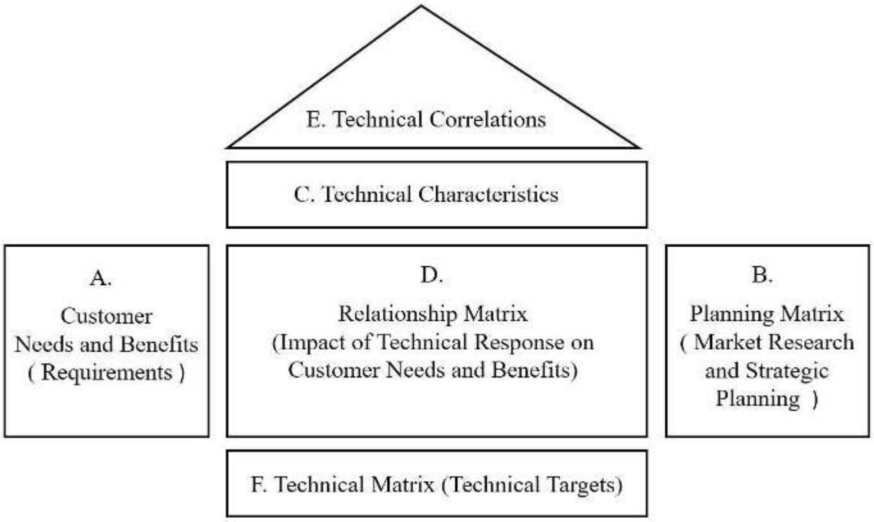


Figure 3.1 The House of Quality (Cohen, 1995)

2.5.2 Application in the construction industry

Many researchers selected QFD as a tool due to the need for improved safety, reliability, delivery, sustainability, and decision-making. Studies identified QFD as a mean for meeting the customers' requirements in construction projects. Also, Mallon and Mulligan (1993) demonstrated that QFD methodology could be used to prioritize different requirements and be a tool for making more accurate decisions. They presented an example of applying QFD to construction using a minor renovation of a computer workroom. Initial customer demands were established and prioritized by customer importance, which was then compared to the competitor's workroom. As a result, the methodology allowed the design team to create ideas while aligning with the customers' demands to reduce future changes. (Mallon and Mulligan 1993).

Alarcón and Mardones et al. (Alarcón and Mardones 1998) applied the methodology of the HoQ to select the technical responses that would be the most effective to avoid the defects in the designs detected in the exploratory study. Dikmen et al. (Dikmen, Talat Birgonul, and Kiziltas 2005) used HoQ as a strategic decision-making tool to design marketing plans in the Turkish house-building sector, resulting in a satisfied company because it considered customer's requirements in a structured way. Delegado-Hernandez (2007) used QFD to analyze and identify customer's requirements by operating a case study comparing a new construction with an existing children's nursery. The use of QFD resulted in on time delivery of the project and higher customer satisfaction.

Several studies with the subjects of sustainability, green buildings, and Leadership in Engineering and Environmental Design (LEED) have also addressed QFD. Shi and Xie (2009) developed a methodology that combined fuzzy set theory and QFD to analyze green construction programs to reduce environmental problems. Gillis and Cudney (2014) applied QFD to ensure that new construction met LEED guidelines, which promote sustainable design and construction. Also, Wood et al. (2016) applied green construction principles with quality function deployment. They proposed a combined approach named House of Quality Green Design for the construction of green hospitals, which facilitate the determination of demanded qualities by end users such as safety mechanisms during an emergency, use of natural light and ventilation, and materials free from toxicity that were environmentally friendly.

Previous research had shown that QFD, could be the right approach to be used in researches that need to align conflicting opinions of customers and when different requirements are needed to be prioritized in decision making.

Therefore, since the objective of this study is to identify the primary retrofit technologies that can fulfill the owner and tenant's requirements by analyzing their needs, QFD seems to be the adequate tool to be used for this research.

2.6 Summary

With the continually increasing rate of the energy used in the construction industry, many countries consider the retrofit process as an excellent method to achieve the targets of energy reduction and sustainable development. Along with the time, extensive studies on retrofit processes have been carried out and have shown that its actions provide not just opportunities to reduce energy but also bring environmental and social benefits. Additionally, considering the energy performance improvement, some of those studies pointed out two critical factors for successful sustainable retrofit activities. These factors are lack of information about the retrofit process and the selection of retrofit technologies to be used in the retrofit process. It can be considered that these factors are a result of the retrofit complex processes usually unfamiliar to stakeholders. Therefore, stakeholders, owners particularly, should have the essential knowledge about sustainable retrofit and technical methods to have an excellent retrofitting performance result. With this, the Energy Performance Certificate can be seen as a reaction to the "information deficit" referring to building owner's lack of knowledge of what retrofit technologies to select and apply in order to enhance the energy performance of their building. The Certificate represents a report on the calculated energy performance of a specific building and its objective is to provide significant information to the owner and act as a catalyst to transform the market mechanism sustainably. To achieve this purpose, the EPC was strengthened with a recommendation report which contains a list of methods to be taken to boost energy savings and encourage stakeholders who have the willingness to retrofit. However, previous studies about the EPCs, show that in its format now, most experts from different countries think that EPCs play a minor role when owners decide to retrofit because the recommendations included are often considered as being too generic, they are not documented by experts, do not suggest system optimization methodologies and scenarios, there is a lack of clear definitions and there is a lack of information about what should be included in the report. Therefore, in its present format, the EPCs cannot reach their full potential in driving energy savings minimizing the information deficit that stakeholders have when retrofitting.

The House of Quality was selected as a tool to address the problem of integrating the varying requirements of the building stakeholders in the decision-making of selecting sustainable retrofit methods. Although the application of House of Quality in the construction industry is limited, several studies have been reviewed, and considerable lessons from those applications have been considered.

Chapter 3. Model development

This chapter attempts to develop a decision-making model that combines the knowledge gained from the preliminary study and which stays true to the objectives of this research.

3.1 House of Quality model for sustainable retrofit

A vital barrier that limits the decision to undergo sustainable retrofitting has been a conflict of interest between stakeholders, due to contrasting perspectives on how and why a building should be retrofitted (Menassa and Baer 2014).

One of the useful guidelines for sustainable retrofit, EPC recommendation report, has a limitation in that it should capture the attention of the owners in order to improve the quality of the result by introducing technical and financial information relevant to the users, such as costs, savings, funding opportunities and how and when to carry out the methods (Gonzalez Caceres 2018). Therefore, this research proposes a model that integrates the stakeholder's interest and their requirements in the EPC's recommendation report which have fundamental guidelines but is required to overcome the barrier of opposition and lack of knowledge concerning sustainable retrofit process.

Stakeholders such as the owner and tenants are responsible for the retrofit design. However, on the one hand, the owner may be interested in achieving a high return on the capital investment with low operating costs while on the other hand, the tenant may be interested in clear incentives such as low rent and comfortability. At the same time, the Accredited Energy Auditor wants to utilize updated technology for fast and efficient repairs, which will improve the sustainability of the building. Furthermore, in some cases, the owner may feel like they are paying for the building upgrades while the tenant is mostly benefiting from reduced energy costs, and the tenants may often think that they are being inconvenienced from the retrofit process that takes place while they are living within that building. Therefore, it is essential to use a tool that integrates all the many stakeholders and their requirements. Also, to know the stakeholder's demands is needed to overcome conflict barriers and to address the interactions between the social, environmental, economic, and technical aspects of the sustainable retrofit process. Hence due to the implication of many stakeholders with different opinions and desires, for this study, seems right to select HoQ as a tool to solve the problem of integrating the varying requirements of the building stakeholders in the decision-making of selecting sustainable retrofit methods, as shown in Figure 3.1. Additionally, with the use of the HoQ model, the study intends to determine a correlation between the building stakeholder demands and considered retrofit technologies. This correlation will help to identify the primary retrofit technologies that should be emphasized in the EPC's recommendation report.

Data needed for the study is collected and examined using an adapted HoQ with five essential steps that provide its general framework, as seen in Figure 3.1. For this study, the Planning matrix was not used. The planning matrix's role is to compare customer requirements of a project with levels of performance or satisfaction for those same requirements on a competitor's building or project and then to set targets for improvement. Since this research is analyzing the retrofit technologies that have the most impact on the decision to undergo a sustainable retrofit, inter-related with the three sustainable pillars, there is no need of planning matrix comparison. Remaining steps in developing the model are explained as followed.

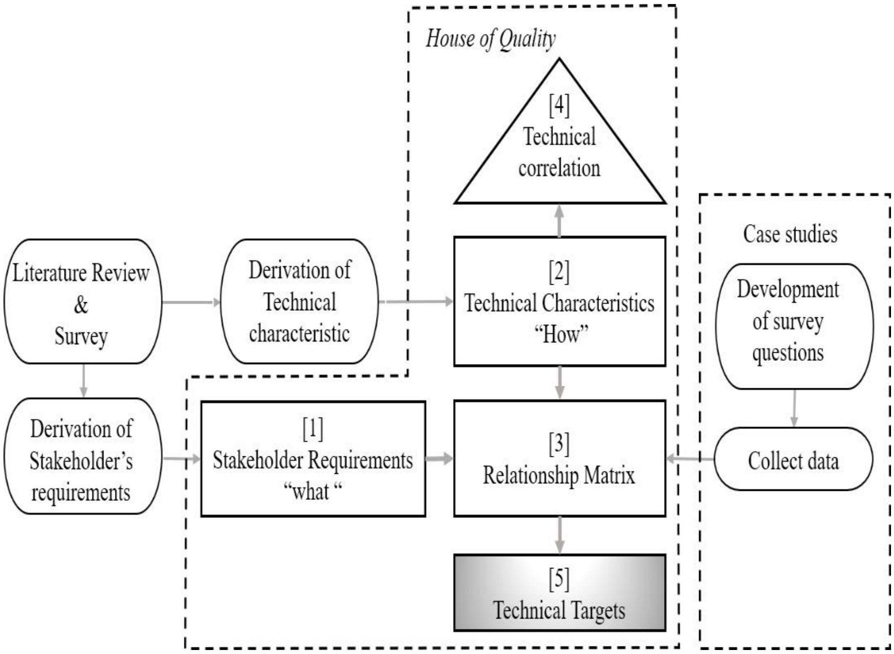


Figure 3.1 Determining Retrofit Technologies process

3.2 Developing the House of Quality model process

Step1. Identifying the possible requirements of the Stakeholders

The first step in developing the model is to identify a list of possible requirements that stakeholders may have when deciding to retrofit the building. These requirements are independent variables and consist of "what" the stakeholders desire to obtain after they retrofit. As in traditional HoQ models, the requirements are limited to the end users, owner and tenant, and can be motivated by social, economic, environmental or technical reasons.

The level of importance of these requirements introduced in a survey is expected to be different among the stakeholders. For example, owners might rank "Reduce energy cost" requirement higher compared to tenants who might place "Improve occupant's health" demand in a higher rank. Depending on the stakeholder's requirements, the technical retrofit methods can change, while owners can be interested in retrofit technologies that can bring economic benefits, tenants might be more interested in technologies to improve the social aspects, as health, productivity or aesthetical quality of the building. The HoQ will translate these differences among stakeholder's requirements by using mathematical formulas. Therefore, the importance of the requirements will be measured on a scale of 1 to 5, while 1 is at the most importance and 5 is at the least importance.

An extensive literature review related to sustainable retrofit was conducted, and 15 potential stakeholder requirements considering the sustainable criterion were identified to be necessary for a sustainable retrofit process, as shown in Table 3.1.

Table 3.1 Potential requirements as discussed in the literature

Sustainable concept	**Stakeholders requirements**	**Reference**
Environmental	Increase energy efficiency	(Poel, van Cruchten, and Balaras 2007; Papadopoulos, Theodosiou, and Karatzas 2002; Juan, Gao, and Wang 2010; Rey 2004)
	Increase carbon neutrality	(Juan, Gao, and Wang 2010; Scofield 2009; Nemry et al. 2010; Gaterell and McEvoy 2005; Papadopoulos, Theodosiou, and Karatzas 2002)
	Facilitate renewable energy	(Papadopoulos, Theodosiou, and Karatzas 2002; Menassa and Baer 2014)
	Meet regulatory requirements	(Fuerst and McAllister 2011; Poel, van Cruchten, and Balaras 2007; Papadopoulos, Theodosiou, and Karatzas 2002)
	Minimize environmental impact	(Scofield 2009; Papadopoulos, Theodosiou, and Karatzas 2002; Lapinski, Horman, and Riley 2006; Juan, Gao, and Wang 2010; Rey 2004)
Economic	Reduce energy cost	(Juan, Gao, and Wang 2010; Rey 2004; Scofield 2009; Papadopoulos, Theodosiou, and Karatzas 2002)
	Increase the return of investment	(Gaterell and McEvoy 2005; Papadopoulos, Theodosiou, and Karatzas 2002; Juan, Gao, and Wang 2010; Rey 2004)
	Increase property value	(Entrop, Brouwers, and Reinders 2010; Bernstein et al., n.d.; Menassa and Baer 2014)
	Improve chances for renting	(Menassa and Baer 2014; Bernstein et al., n.d.; Fuerst and McAllister 2011)
	Achieve lower total ownership costs	(Juan, Gao, and Wang 2010; Menassa and Baer 2014; Entrop, Brouwers, and Reinders 2010; Scofield 2009; Fuerst and McAllister 2011)
Social	Improve occupant's health	(Rey 2004; Lapinski, Horman, and Riley 2006; Klotz and Horman 2009; Menassa and Baer 2014).
	Improve occupant's comfort	(Rey 2004; Lapinski, Horman, and Riley 2006; Klotz and Horman 2009; Menassa and Baer 2014)
	Improve occupant's productivity	(Klotz and Horman 2009; Menassa and Baer 2014)
	Improve the aesthetic quality of the site	(Rey 2004; Bernstein et al., n.d.; Menassa and Baer 2014)
	The necessity to comply with policy or legislation	(Menassa and Baer 2014; Poel, van Cruchten, and Balaras 2007; Papadopoulos, Theodosiou, and Karatzas 2002)

The chosen requirements were divided into three categories: social, economic, and environmental. Although some of these requirements appear to have the same meaning, they are independent variables and they were selected because they may have a different meaning for different stakeholders. For example, “Meet regulatory requirements” and “The necessity to comply with policy or legislation” appears to mean the same thing. However, some stakeholders may be more concerned with meeting the regulations to mitigate global environmental impacts while other stakeholders may be motivated to comply with the policy or legislation regardless of the environmental benefits.

The primary role of the analysis of the stakeholder's requirements is for them to rate each need based on its importance in addition to defining the scope of a project. In this research, each requirement is seen as the benefit resulting from possible sustainable retrofit actions. The importance rating for each stakeholder requirement it is defined as the importance of each requirement in justifying the investment of resources into a retrofit project. This total importance rating for each stakeholder requirement is independent of the total technical importance for the retrofit technologies in meeting the various demands of the stakeholders.

Step2. Identifying the retrofit technologies that can fulfill the stakeholder's requirements

The second step in developing the model is to identify the technical methods that can fulfill the stakeholder's requirements. The technical matrix represents the design response as “how” some retrofit technologies will meet the needs of the stakeholders.

When choosing among a variety of proposed methods, the decision maker must reconcile environmental, energy-related, financial and legal regulation and also social factors to reach the best possible compromise to satisfy the final occupant needs and requirements (Asadi et al. 2012). In order to determine the technical methods to be included in the model, a literature review was conducted. The Building Research Establishment defines the main components on which refurbishments are made as thermal elements such as walls, roofs, and floors; fittings such as windows and entrance doors and building services like lighting, heating, and cooling; and the operation of pumps (Li, Ng, and Skitmore 2017). Asadi et al. (2012) and Desmedt et al. (2009) show in their studies the importance of considering building envelope as a technical issue during building retrofit. Additionally, a study about the transformation through renovation of an apartment building in Athens concluded that significant energy efficient solutions are energy efficient lighting by using LED and light pipes, energy efficient HVAC, passive heating/cooling, heat pumps integrated with heat recovery and thermal storage and renewable energy systems based on solar thermal and photovoltaics (Synnefa et al. 2017).

For better structure, the chosen technologies were organized according to the interventions made for the mechanical system, electrical system, plumbing system, and building envelope. The detailed list can be seen in Table 3.2

Table 3.2 List of Retrofit Technologies

Mechanical System	**Electrical system**	**Plumbing system**	**Building envelope**
Replacement of Heating system and Air Conditioning system	Lighting fixtures	Replacement of Domestic hot and cold-water system	Applying an external thermal insulation system
Replacement of Water heating system	Replacement of Electrical system	Recycling methods of residual water	Replacement of windows and doors
			Roof renovation

Step 3. Development of the relationship matrix

The primary purpose of the relationship matrix is to establish a connection between the stakeholder's requirements and the technical methods applied. Additionally, it highlights which retrofit technology supports the fulfillment of each stakeholder's demands. The relationship between the requirements and the technical methods is weighed on a scale of 0-relationship, 1-weak relationship, 3-medium relationships, and 9-high relationships. For example, an expert may think that "replacement of Heating system and air conditioning system" has a high ability to increase energy efficiency, while another expert may consider it to have a small capacity of increasing energy performance.

The development of the relationship matrix will be perceived through two surveys. The first survey will analyze the importance of the requirements from the owner's and tenant's perspective. The second survey will investigate the potential of each technical method in fulfilling the stakeholder's needs from an expert's perspective. The importance ratings from these surveys are calculated into a technical importance factor given by equation (1):

$$\mathrm{T_I} = \text{Importance of requirement} \cdot \text{Relationship} \quad (1)$$

where T_I means Technical importance

Step 4. Developing the Technical Correlation Matrix

The technical correlation matrix aids in the development of the relationship between the technical methods and identifies where these units must work together; otherwise, they will be in a design conflict. This component, the roof, it is one of the most valuable parts as it represents the effects, either negative or positive, each retrofit technology has on another. It offers a quick visual for an Accredited Energy Auditor and owner to understand the impacts one retrofit technology will have on another technical method. This can also provide a quick reference for any Auditor to realize that communication with another auditor or engineer may be necessary especially if a negative effect is found in the cell.

Some retrofit technologies suggested by the Accredited Energy Auditor may affect or impact more than one retrofit technology option. In this situation a chain reaction of impacts can occur, therefore discussion among the involved stakeholders will be necessary to solve possible design conflicts. For example, the retrofit technology "Roof renovation" exposes several relationships that should be considered. There are many design strategies that may be applied to improve the performance of the roof, but let's consider the "green" roof option. First, when the Accredited Energy Auditor will propose a "green" roof renovation, he should compare the cost to install a "green" roof with a more conventional roof which will also accomplish with the owner's desire (budget impact). Second, the "green" roof option will likely have a greater mass and may require an evaluation of the structural system of the building (budget impact and possibility of necessity of action to be taken at structural level).

Therefore, the Auditor who performs the examination of the building and suggests the retrofit technologies to be included in the EPC report should propose changes which will not be in conflict with each other. For example he can propose a type of insulation for the roof that will not impact the budget or affect the structural system of the building, but rather will reduce the heating and cooling loads on the building, therefore, reduce the amount of energy required to maintain thermal comfort. This improvement will also reduce the required equipment to heat and cool the building, therefore energy savings and cost reduction.

Hence, when working with the technical correlation matrix to clarify the relationship among requirements, the question "If technical requirement X is improved, will it help or hinder technical requirement Z? " needs to be addressed (Jennifer Tapke Greg Johnson Josh Sieck 2013). The following symbols are used to represent what type of impact each requirement has on the other: + positive correlation, . no correlation, and - negative correlation.

Step 5. Developing the Technical Targets Matrix

The technical targets represent the final output of the matrix, and they are obtained calculating the relative weights of the technical methods with equation (2). The obtained value is used for a decision-making comparison.

$$\text{Relative weight} = \left(5 \cdot \frac{\sum T_I}{Max(\sum T_I)}\right) \quad (2)$$

The technical method with a relative weight equal to 5.00 represents the most crucial consideration to focus on the recommendations included in the EPC.

3.3 Summary

The general framework of the House of Quality used for this research has five essential steps: (1) Identifying the possible requirements of the Stakeholders, (2) Identifying the technical methods that can fulfill the stakeholder's requirements, (3) Development of the relationship matrix, (4) Developing the Technical Correlation Matrix, and (5) Developing the Technical Targets Matrix. The first steps have a role in identifying the necessary information to be used for the 3rd step, the relationship matrix, which has the purpose of establishing a connection between the stakeholder's requirements and the technical methods applied. Its output is expressed in the technical matrix. The technical correlation matrix aids in the development of the relationship between the technical methods. Analyzing the final output technical method with a relative weight equal to 5.00 will represents the most crucial retrofit technology to be taken into consideration.

Chapter 4. Case Studies

In this chapter a case study with the proposed method, using the House of Quality was conducted in Romania to reveal the necessary technical methods that can fulfill the needs that owners and tenants of a residential building have when retrofit. The case study illustrates how the House of Quality is used stepwise, and its result can be used to improve the Energy Performance Certificate in Romania.

4.1 Background of Case Study

Romanian buildings stock accounts for the largest share of energy use, which is mainly due to their overall poor energy performance. The household sector and the tertiary sector, together, accounted for 46% of total national energy consumption. Up to 80% of the CO_2 emissions from the Romanian building stock could be reduced through a comprehensive renovation program (Arcipowska et al. 2014). Therefore, Romania needs a rapid enhancement of energy efficiency in existing buildings for a timely reduction in energy use.

As a Member State of the European Union, Romania needs to meet the requirements imposed by the European Commission regarding energy consumption in buildings. Therefore, in 2001 the Romanian government adopted the Energy Performance Certificate as a voluntary system, following the transposition of the Energy Performance of Buildings Directive (EPBD) into national law in 2005, and the revision in 2013 and 2016. The Romanian EPC is mandatory for new and existing buildings when either sold or rented and the compliance control is conducted only by checking the form and information within the EPC (Buildings Performance Institute Europe 2018). The EPC contains information about specific energy consumption related to space heating, domestic hot water installations, lighting, mechanical ventilation, and space cooling. This information is enough to evaluate the energy performance of the certified building, but the detailed technical information, which should be provided in the EPC's annex, is often incomplete and retrofit recommendations often are missing. To enhance the EPC's value, changes in the format of EPC and the system are required. Hence, by this case study, it is intended to shape a better structure of the Romanian EPC by improving the recommendations part, taking into consideration the owner and tenant's opinion.

4.2 Survey

4.2.1 Survey Development

To investigate the requirements that Romanian owners and tenants have, and the retrofit technologies which have an impact on those requirements, two descriptive web surveys were conducted. Appendix A and C

Step1. Investigating the stakeholder's requirements for the retrofit process: Stakeholder's survey

The first survey had a role in studying the primary needs of the Romanian owner or tenant when they retrofit. More precisely it addressed the following research question: Which requirements boost owners and tenants to retrofit? The structure of the questionnaire was designed in three different sections: (1) occupier's background, (2) building background and (3) requirement's importance ranking considering the three pillars of the sustainability: environment, economic and social. In the case of the rating questions, the option to "Randomize Rows for Each Respondent" was activated to make sure the order implied by the researcher will not influence the respondent's choices. The indexes assigned for the ranking were from 5 to 1, with 5 to be an extremely important need and 1 to be not an important need. The parameter of sampling interest was from the population of residential buildings and the sampling frame comprised the occupiers of the house from different areas of Romania. The unit of analysis were the individual, and the sampling size was determinate based on the target population, represented in this case just by owners and tenants. The questionnaire was accessed by 238 people with 152 complete and valid answers.

Among the 152 respondents, 67.11% were owners, and 32.89% were tenants. Regarding the owner's propriety, 54.90% own an apartment, 39.22% one family dwelling and 5.88 % multiple family dwelling. In the tenant's case, 80% were tenants of an apartment, 14% of a family dwelling and 6% of a multiple family dwelling. When asked if they possess an EPC, 29.61% of the respondents answered that they do possess an EPC, 39.47% do not have an EPC, and 30.92% declared that they do not know if they possess or not an EPC. Among those who have an EPC, the EPCs class were A 40%, B 13.33 %, C 13.33%, E 2.22%, F 2.22 % and 31.11% Unknown class.

For a better understanding of the building stock, the respondents were asked in which year was the building build and when it was renovated last time. The results show that 6.58% of the buildings were built before 1950, 9.87% between 1950-1969, 48.68% between 1970 - 1989, 16.45 % between 1990 - 2009, and 18.42 between 2010 - 2018. It can be concluded that most of the buildings from this study, 65,13%, were built before 1990. This aspect highlights the importance of retrofitting in Romania. Regarding the situation of renovation, 23.68% of buildings were never renovated, 46.04% were renovated between 1 and 4 years ago, 16.45% were renovated between 5 and 10 years ago, and 13.82% more than 10 years ago

The results (Appendix B) of the survey were combined into an average data that was introduced on the left side of the relationship matrix as seen in Figure 4.1

Step2. Identifying the retrofit technologies that can fulfill the stakeholder's requirements: Accredited Energy Auditor's survey

The second survey had a role in studying the primary retrofit technologies which can fulfill the needs of the owners and tenants. More accurately it addressed the following research question: Which retrofit technology has the most significant impact in satisfying what the owner or tenant expects to achieve as a result of the retrofit process? The questionnaire was sent through email, accompanied by an abstract of the research study.

The structure of the questionnaire was divided into two parts: (1) the expert's background and (2) a study of the relationship between the retrofit technologies and stakeholder's demands. The respondents were asked to grade the relationship between the retrofit technologies and their potential for fulfilling the stakeholder's requirements. When grading the technical method, the system type (mechanical, electrical and plumbing system, and building envelope) and sustainability concepts: environmental, economic and social, had to be considered. The indexes assigned for the relationship were 9-3-1-0, indicating a high relationship, a medium relationship, a weak relationship or no relationship. The sampling for this survey was purposive, and the respondents were experts who have working experience with Energy Performance Certificates and are Accredited Auditors to carry out energetic examinations on existing buildings. The target population was represented by 1000 accredited energy auditors certified as energetic auditors until 19 September 2018 by Romanian's Ministry of National Development and Public Administration. 36 persons returned the questionnaire, with 25 complete and valid responses.

Among the 25 experts who assessed the survey 12% have less than 10 years working experience in construction, 72% have between 11 and 20 years of experience, and 16% more than 21 years. The experience working as an accredited energy auditor of the participants was 28% less than five years, 64% between 5 and 10 years and 8% more than 10 years of experience.

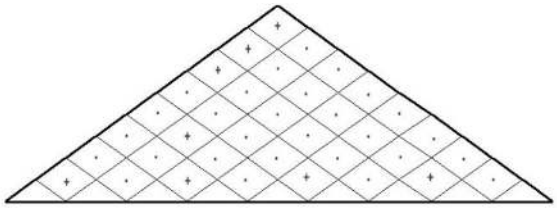
Specific results can be seen in Appendix D.

4.2.2 Analyzing data collected from the survey

The results of the surveys were combined into an average data and introduced in the HoQ rooms as seen in Figure 5.1. The first survey results on the left side of the HoQ, in the "Stakeholder's requirement" room, and the second survey's results in the relationship matrix room.

In order to develop the relationship matrix, the technical importance of each retrofit technologies was calculated by multiplying stakeholder's importance rating by the relationship defined by the experts. The next step after developing the relationship matrix was to check the technical correlation between the technical method proposed. The objective of this step is to highlight any methods that might conflict with each other. In this case, however, as it can be seen in Figure 4.1, no negative correlation was identified between the technical methods, and only positive one or no correlation was interpreted.

The technical targets represent the final output of the matrix. These technical targets were obtained by calculating the relative weights of the technical methods. After the technical importance for each method was obtained the sum of technical importance was calculated for each of it. The sum was then equated into a single value on a scale of 1 to 5, as it can be seen at the bottom of Figure 4.1. This scale represents a prioritized relative weight for a decision-making comparison.



First survey results | Second survey results $T_I = Importance\ of\ requirement \cdot Relationship\ (SR)$

No.	Category	Stakeholder importance rating (Importance of requirement)	Technical Requirements (How) → / Stakeholder Requirements - (What) ↓	Mechanical System				Electrical system				Plumbing system				Building envelope					
				Replacement of Heating system and air conditioning system		Replacement of Water heating system		Lighting fixtures		Replacement of Electrical system		Replacement of Domestic hot and cold-water system		Recycling measures of residual water		External thermal insulation system		Replacement of windows and doors		Roof renovation	
				S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I	S.R	T.I
1	Environmental	3.70	Increase energy efficiency	7.08	26.17	5.96	22.03	5.52	20.40	3.76	13.90	5.36	19.81	3.24	11.97	8.76	32.38	8.28	30.60	7.96	29.42
2		2.48	Increase carbon neutrality	4.64	11.50	3.92	9.72	3.36	8.33	3.04	7.54	3.40	8.43	2.60	6.45	6.24	15.47	6.44	15.97	4.96	12.30
3		2.62	Facilitate renewable energy	5.04	13.21	4.84	12.68	3.28	8.59	3.68	9.64	3.64	9.54	2.72	7.13	4.04	10.59	3.72	9.75	4.00	10.48
4		3.05	Meet regulatory requirements	4.96	15.14	4.92	15.02	3.92	11.97	3.36	10.26	4.36	13.31	3.80	11.60	6.28	19.17	6.20	18.93	5.24	16.00
5		3.15	Minimize environmental impact	5.12	16.14	4.96	15.63	4.36	13.74	3.04	9.58	3.56	11.22	3.96	12.48	5.80	18.28	5.32	16.77	4.88	15.38
6	Economical	3.80	Reduce energy cost	5.72	21.74	6.04	22.96	6.60	25.09	4.36	16.57	5.84	22.20	3.68	13.99	8.44	32.08	8.44	32.08	7.88	29.96
7		2.59	Increase return of investment	4.8	12.41	4.8	12.41	3.80	9.83	2.84	7.35	3.56	9.21	2.56	6.62	5.92	15.31	5.32	13.76	5.24	13.55
8		3.11	Increase property value	4.56	14.20	4.36	13.58	3.12	9.72	3.84	11.96	4.16	12.96	3.24	10.09	7.08	22.05	6.84	21.30	5.68	17.69
9		2.25	Improve chances for renting	4.84	10.87	4.36	9.79	3.84	8.62	4.04	9.07	3.88	8.71	2.92	6.56	7.08	15.90	6.92	15.54	5.08	11.41
10		3.26	Achieve lower total ownership costs	5.72	18.64	6.04	19.69	4.56	14.86	3.92	12.78	5.20	16.95	3.72	12.13	7.16	23.34	7.40	24.12	6.12	19.95
11	Social	4.00	Improve occupant's health	4.64	18.57	4.20	16.81	4.00	16.01	3.40	13.61	4.72	18.89	2.88	11.53	4.92	19.69	5.68	22.73	4.32	17.29
12		3.47	Improve occupant's comfort	6.52	22.60	5.24	18.16	4.60	15.95	4.40	15.25	5.32	18.44	2.64	9.15	7.60	26.35	7.12	24.68	6.44	22.32
13		2.39	Improve occupant's productivity	4.2	10.02	3.48	8.30	4.28	10.21	3.32	7.92	3.56	8.49	1.92	4.58	5.20	12.40	5.28	12.59	3.64	8.68
14		2.21	Improve esthetic quality of site	3.32	7.35	2.48	5.49	3.16	7.00	2.48	5.49	2.72	6.02	2.00	4.43	5.96	13.19	6.80	15.05	6.20	13.73
15		2.93	Necessity to comply with policy or legislations	4.84	14.16	4.00	11.70	4.28	12.52	4.64	13.57	4.16	12.17	3.76	11.00	6.76	19.77	6.28	18.37	6.52	19.07

	Replacement of Heating system and air conditioning system	Replacement of Water heating system	Lighting fixtures	Replacement of Electrical system	Replacement of Domestic hot and cold-water system	Recycling measures of residual water	External thermal insulation system	Replacement of windows and doors	Roof renovation
Technical importance score (T.I)	232.73	213.98	192.83	164.48	196.35	139.70	295.97	292.25	257.22
Importance %	12%	11%	10%	8%	10%	7%	15%	15%	13%
Relative Weight	3.93	3.61	3.26	2.78	3.32	2.36	5.00	4.94	4.35
Priority rank	**4**	**5**	**7**	**8**	**6**	**9**	**1**	**2**	**3**

Figure 4.1 House of Quality

4.3 Findings of Case Study

4.3.1 Priority rank of Retrofit Technologies

The primary output of the HoQ is the highlight of the five most critical retrofit technologies which have significant potential to fulfill owners and tenants' requirements when deciding to retrofit.

Table 4.1. Results of the case study

Retrofit technologies		Technical importance score (T.I)	Importance (%)	Relative Weight	Priority rank
Mechanical System	Replacement of Heating system and air conditioning system	232.73	12%	3.93	4
	Replacement of Water heating system	213.98	11%	3.61	5
Electrical system	Lighting fixtures	192.83	10%	3.26	7
	Replacement of Electrical system	164.48	8%	2.78	8
Plumbing system	Replacement of Domestic hot and cold-water system	196.35	10%	3.32	6
	Recycling methods of residual water	139.70	7%	2.36	9
Building envelope	Application of an external thermal insulation system	295.97	15%	5.00	1
	Replacement of windows and doors	292.25	15%	4.94	2
	Roof renovation	257.22	13%	4.35	3

The results achieved in Table 4.1 demonstrated that the five most essential retrofit technologies which can contribute to the success of energy efficiency and satisfy the owners at the same time are: (1) application of an external thermal insulation system, (2) replacing the existing windows and doors, (3) roof renovation, (4) replacement of the heating system and air conditioning system and (5) replacement of the water heating system. These points should be highlighted during the development of EPC's recommendation report as they have a higher potential to fulfill the needs valued by the users.

The calculations performed to find the weights of stakeholder's needs are essential to highlight the demands that require attention. According to the obtained results, the three most essential stakeholders' demands have been ranked as "Improved occupant's health," "Reduce energy cost" and "Increase energy efficiency."

Moreover, if the relationship matrix of the HOQ matrix given in Figure 4.1 is investigated:

column-wise, the significance and contribution of each technical method in satisfying overall stakeholder needs can be seen. The technical methods, namely "application of an external thermal insulation system," replacing the existing windows and doors" and "roof renovation" can have the highest contribution in the overall success of a project.

row-wise, the contribution of all the technical methods in satisfying the stakeholder's needs is observed. The stakeholders need namely; "Increase energy efficiency," "Reduce energy cost" and "Improve occupant's comfort" have been linked with the highest number of technical methods. So, they have been the owner/tenant's expectations that could be handled with the highest number of proposed technological methods.

Analyzing the model by sustainable pillars, as it can be seen in Table 4.2, an average relative weight of 5 was given for economic, followed by 4.61 for the environmental and 4.38 for the social impact. Moreover, stakeholders perceive the “environmental” aspect as a more important outcome of the retrofit process when compared with social benefits like ‘improving occupant’s productivity’ or ‘improving the aesthetic quality of the site.’ Furthermore, the stakeholders indicate the following needs as having the lower importance as principles behind their sustainable retrofit goals: Economic: ‘Improve chances for renting’ and ‘Increase return of investment’; Environmental: ‘Increase carbon neutrality’ and ‘Facilitate renewable energy’; Social: ‘Improving the esthetic quality of the site’ and ‘Improve occupant’s productivity’.

Table 4.2 Importance by Sustainable Concept

Sustainable concept	Stakeholders requirements	T. I	∑T. I	Relative Weight
Environmental	Increase energy efficiency	206.67	654.59	4.61
	Increase carbon neutrality	95.70		
	Facilitate renewable energy	91.60		
	Meet regulatory requirements	131.39		
	Minimize environmental impact	129.23		
Economic	Reduce energy cost	216.68	709.58	5.00
	Increase the return of investment	100.45		
	Increase property value	133.54		
	Improve chances for renting	96.46		
	Achieve lower total ownership costs	162.45		
Social	Improve occupant's health	155.14	621.33	4.38
	Improve occupant's comfort	172.91		
	Improve occupant's productivity	83.19		
	Improve aesthetic quality of the site	77.75		
	The necessity to comply with policy or legislation	132.34		

4.3.2 Comparison between Sustainable Concept

In this section, the priority rank of retrofit technologies concerning social, environmental, and economic considerations were evaluated. This evaluation was performed to determine which retrofit technologies are most important in delivering beneficial impacts on each sustainable consideration.

As it can be seen in Figure 4.2, retrofit technologies that belong to building envelope category have the highest potential in fulfilling stakeholder's requirements for every sustainable consideration. It can be mentioned that for Environmental and Economic groups the application of external thermal insulation has the most significant impact, while for Social aspects replacement of windows and doors action has a more considerable effect on fulfillment of stakeholder's requirements. These two technologies are followed by "Roof renovation" with a relative weight of 4.36 for Environmental, 4.34 for Social, and 4.26 for Economic consideration.

The second system in the ranking is the Mechanical System. Both retrofit technologies from this group have a significant impact on the environment; however the replacement of heating and air conditioning system has a higher positive effect, with a relative weight of 4.28. The replacement of water heating system represents the fourth essential impact for Economic , relative weight 3.61, and fifth place for Social, relative weight of 3.24, while the replacement of heating and air conditioning system occupies the fourth place for Social with a relative weight of 3.89 and fifth rank for Economic consideration.

The replacement of the domestic hot and cold water system occupies the sixth rank for all sustainable consideration groups, economic, environmental, and social, being followed by the lighting fixtures, replacement of electrical system and recycling measures of residual water as the retrofit technology with the smallest impact on satisfying statehooder's needs .

It was demonstrated in this case study that the retrofit technologies related to envelope actions are essential in delivering beneficial impacts on each sustainable consideration; however, the harmony between social, environmental, and economic factors is not substantially out of balance, the deference between relative weights being quite small.

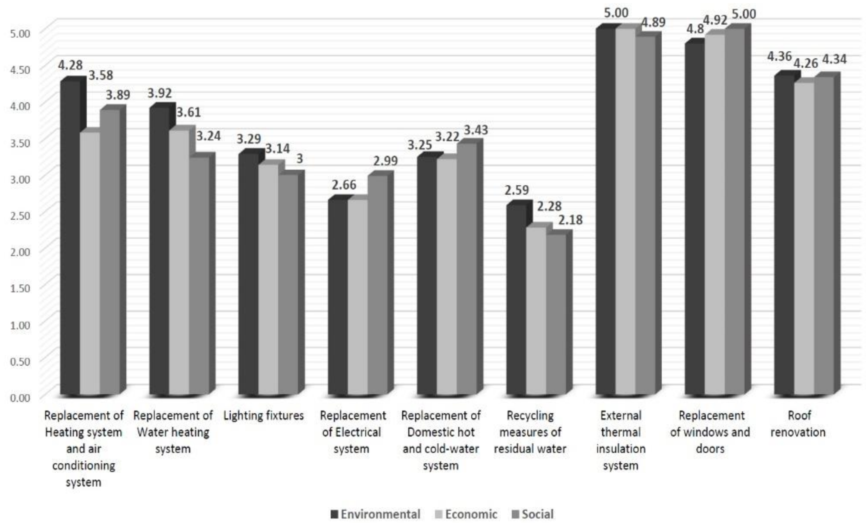


Figure 4.2 Comparison of Priority Ranking by Sustainable Concept

4.3.3 Comparison between Owner and Tenant's results

Using a multi-attributed approach, the House of Quality compares relative weights resulted from different groups of participants in the survey. By analyzing the comparison between various stakeholders' opinion, this research intends to determine if there are differences between the perceptions of different groups of stakeholders participating in the study case, rather than deciding if the results are representative for a specific group of stakeholders.

The technical targets matrix is a useful tool in translating many competing stakeholder requirements into functional focus areas and contains essential information concerning the view of the different stakeholders regarding what retrofit technologies are most important to satisfy their sustainable retrofit requirements. Therefore, to analyze where a conflict between owners and tenants may exist, a HOQ analysis was made separately for each group. The same steps made to determine the priority rank for all stakeholders were followed for analyzing responses provided by individuals within each of the tenants and owners stakeholder. The technical importance and priority rank are presented in table 4.3.

Table 4.3 Technical Targets Matrix Results: Comparison by Stakeholder

Technical Requirements (How)	**Technical Importance**		**Relative Weight**		**Priority rank**	
	T	**O**	**T**	**O**	**T**	**O**
Mechanical System						
Replacement of Heating system and air conditioning system	231.94	232.73	3.93	3.93	4	4
Replacement of Water heating system	231.23	214.22	3.61	3.62	5	5
Electrical system						
Lighting fixtures	192.04	193.12	3.25	3.26	7	7
Replacement of Electrical system	164.45	164.41	2.79	2.78	8	8
Plumbing system						
Replacement of Domestic hot and cold-water system	195.14	196.84	3.31	3.32	6	6
Recycling measures of residual water	139.72	139.61	2.37	2.36	9	9
Building envelope						
External thermal insulation system	**295.13**	**296.2**	**5**	**5**	**1**	**1**
Replacement of windows and doors	291.02	292.65	4.93	4.94	2	2
Roof renovation	255.78	257.78	4.33	4.35	3	3

*T-Tenant; O-Owner

A graphical representation of table 4.3, summary of retrofit technologies target data, is provided in Figure 4.3 to compare how much technical importance each group of stakeholders placed on each retrofit technology.

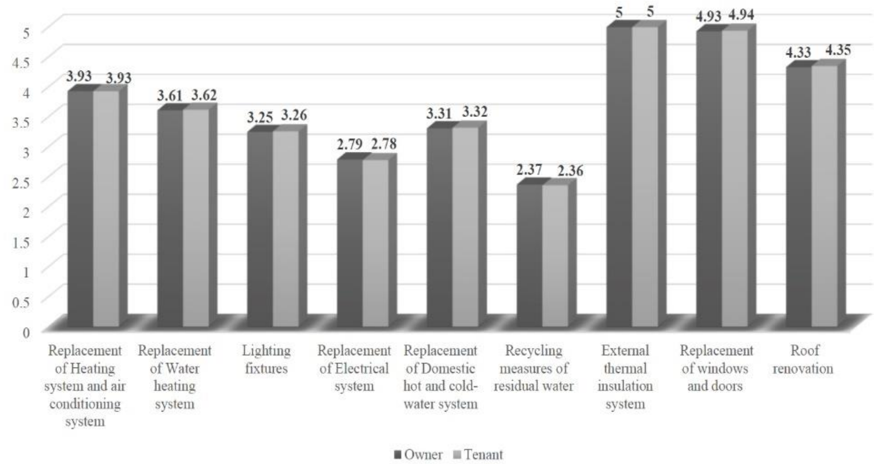


Figure 4.3 Comparison of relative weight: Owner versus Tenant

As it can be observed in Figure 4.3 with little difference in relative weights, for both groups, owners, and tenants the retrofit technologies from building envelope have the highest potential in meeting stakeholders' sustainable retrofit requirements. Technologies related to the mechanical system also received a high rating for technical importance, with relative weights that ranked the mechanical system as the second most important system to address when issuing the EPC's recommendation report. The electrical system and the plumbing are following in ranking for both the owner and tenants as the third and fourth important system, with the mention that the retrofit technology "Replacement of Domestic hot and cold-water system" was considered to have more potential to fulfil stakeholders' requirements than the electrical system's technologies.

By comparison of the final HOQ technical targets matrix results for each individual stakeholder group, another level of analysis can be made. This analysis can illustrate how the HoQ can be used to find where conflict may appear among different stakeholders that participate in developing the recommendation report. Although this comparison demonstrated that owners and tenants agree concerning the ranking of the retrofit technologies that can fulfill sustainable requirements when adding more stakeholder groups, as managers and designers, or having a different social background the results may be different. Therefore, in practice, when using this model, conflicts that may appear can be analyzed more quickly and taken into consideration.

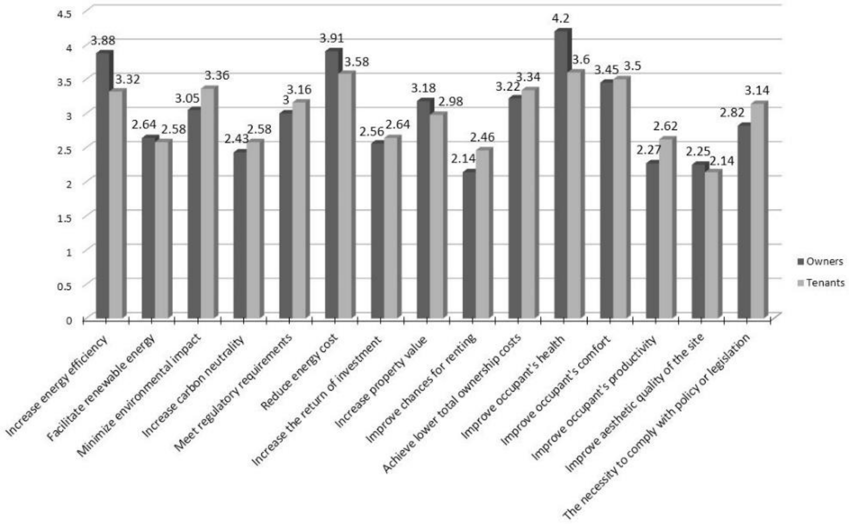


Figure 4.4 Comparison of Importance Rating: Owner versus Tenant

Throughout this research, owners and tenants were introduced as having different opinions and demands when they decide to retrofit. Therefore, an important objective of this research was to align their desires and mitigate the conflicts that may appear due to disagreement. For example, the owner of the building may be mainly interested in the requirements related to the economy as increasing the propriety value while the tenants may be interested in incentives such as lower operating costs, improve occupant comfort and increase their productivity.

It can be seen in Table 4.3 on page 49 that the tenants and the owners have similar results for retrofit technologies priority and that there were no significant disagreements to note. However, the discrepancy may still exist concerning the principal reasons to retrofit sustainable in different case study building, regardless of the retrofit technologies focus areas that were agreed to be applied. In this case study, Figure 4.4 shows that owners and tenants are in generally in agreement related to the ranking of the importance of each requirement. The tenants do feel that improving comfort and productivity, mitigate the environmental impact and compiling with the imposed regulations are more important than the owners perceive; however, still, requirements related to saving energy and reducing costs occupy an important rating.

Both the owner and tenant agree that improving occupant's health and reducing energy costs are the most important sustainable retrofit objectives, and that improving chances for renting and the aesthetic quality of the site are the last important when they decide to retrofit. Therefore, the tenants and owners in this case study have demonstrated that they are also aligned in their sustainable retrofit requirements.

4.3.4 Validation of results

The literature review about retrofit processes shows that the retrofit technologies which can have the biggest impact on saving energy and may improve the overall performance of the building can be categorized in three main strategies ranked as followed: (1) actions regarding envelope and design aspects including insulation upgrades, air leakage reduction and improving of doors and windows; (2) actions for building systems as HVAC systems, improvement of electrical lighting systems and improvement of domestic appliances; (3) activities associated with building services and management tools.

To validate the results of HoQ, an analysis of the expert's answer was conducted to determinate the ranking importance of retrofit technology. The results of the investigation were compared with findings from the literature review. As can be seen in Figure 4.4, the experts considered that the retrofit technologies related to building envelope are the essential retrofit actions to be performed to achieve good energy performance of the building. In this category actions related to "External thermal insulation system" occupy the first place with 0.75 relative weight, followed by "Replacement of windows and doors" and activities as "roof renovation" with relative weight as 0.74 and 0.65. The second place is taken by the mechanical system with a relative weight of 0.59 for "Replacement of Heating system and air conditioning system" and 0.54 for "Replacement of Water heating system." Followed by the electrical system and plumbing system.

Comparing these results with the literature review findings, it may be concluded that the results from the HoQ can be taken into consideration and validated due to similar results. However, it needs to be specified that the validation has its limitation because of the expert's social background. This is an important aspect and needs to be taken into consideration when comparing the results. For example, the retrofit technology related to "Recycling measures of residual water" occupies the last place with a relative weight of 0.35 for the case study due to social reasons. In Romania recycling measures of residual water are not often applied. Therefore, the experts may have been influenced by this aspect while grading the importance of each retrofit technology.

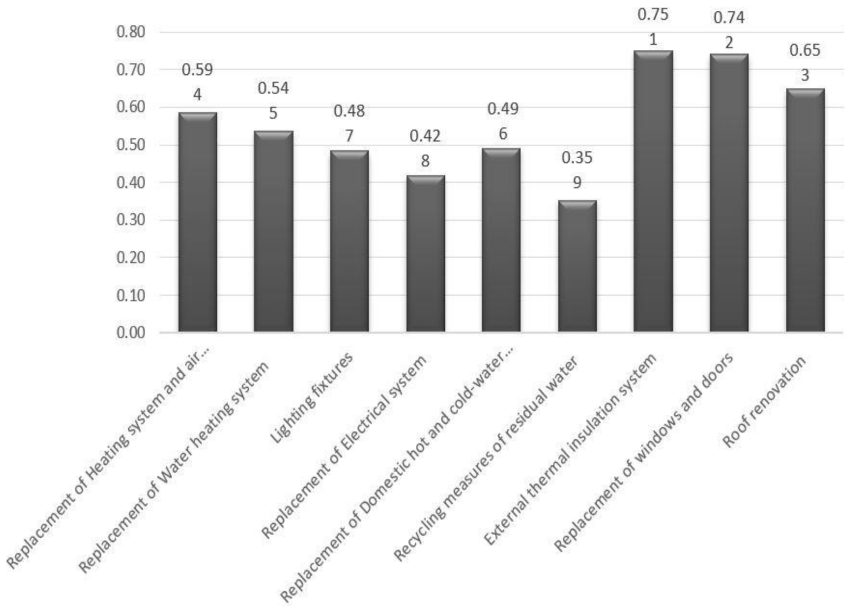


Figure 4.5 Retrofit technology ranking importance by experts

4.4 Discussions

This research presents a model for identifying the retrofit technologies which should be highlighted in the Energy Performance Certificate recommendation report, in order to boost the energy performance of the existing buildings. The interest of stakeholders during the retrofit process should be considered when choosing the retrofit technologies for the recommendation report, mostly because they play an essential role in determining how, why and if the retrofit methods will be implemented. Decision-making support towards sustainable renovation would cause dialogues between stakeholders, and it also contributes to facilitating communication between practitioners from various professional fields and property owners, which is necessary to identify and balance all the values (Thuvander et al. 2012). The retrofit process produces a range of environmental, social and economic benefits (D. Brown, Sorrell, and Kivimaa 2019). It has been shown to improve not just energy efficiency but as well the occupant health and wellbeing (Willand, Ridley, and Maller 2015). Also, it produces unique benefits to owners, including increased property value, significant savings in energy bills and improved thermal comfort (Aravena, Riquelme, and Denny 2016). However, the majority of stakeholders are not aware of the proportion of these benefits and may overlook future benefits, resulting in a reluctance to make investments in energy efficiency improvements (Frederiks, Stenner, and Hobman 2015; Aravena, Riquelme, and Denny 2016).

Considering that stakeholders as individuals have various perception and motivation to retrofit, their perceived importance of the three sustainable concepts will be different as well, corresponding to each owner's need. Thus, the selection of the retrofit technologies should reflect these differences; for example, if the owner's motivation is to obtain environmental benefits, methods such as "recycling of residual water" or "renewable energy "should be first considered before other methods. On the other hand, if the owner prioritizes the social drivers as comfort and productivity, then the decision-maker and the energy auditor should also prioritize the application of retrofit technologies as replacement of heating system and air conditioning system, which can significantly improve the thermal comfort of the occupant. All these aspects need to be considered by the decision making in developing the recommendation report and selecting the best retrofit technologies to be applied. Therefore, the model of HoQ presented in this study can be used as a tool to analyze different scenarios and obtain the critical combination of retrofit technologies.

Moreover, this model can give insights about which of the three pillars of sustainability motivates the most an owner in the retrofit process. For example, although the motivation to encourage building retrofits at the government level is to reduce the adverse effect of excessive energy use on the global environment, economy and human health, the case study showed that the main reason to motivate stakeholders to retrofit is the economic aspect, in reality. Therefore, it can be concluded that the retrofit technologies included in the report would fulfill the financial requirements first and easily neglect the social and environmental aspects due to the risk of the final decision to be dictated by economic incentives. Hence, when using the proposed model, a combination of all the requirements should be taken into consideration.

The EPC recommendation report intends to provide valid support for the building owner to make it easier for him/her to decide the retrofit methods. This report can be issued standard or in the form of a tailor-made list of actions. As presented in Figure 4.3 in order to obtain a reliable EPC and tailor-made recommendations, it is essential that an AEA inspects the building and gets information concerning the construction, technical systems, and stakeholder's needs. This study suggests to the building inspection representative (AEA) that using the proposed HoQ model to analyze stakeholder's needs will allow to better incentives for them to retrofit. The stakeholder, together with the expert, will participate actively in the process of selecting the retrofit technologies. As a result, they will recognize more readily available retrofit methods which should be applied for a better retrofit performance.

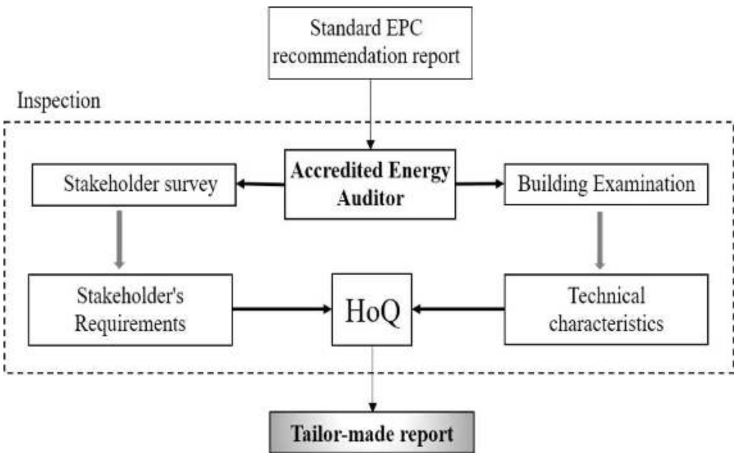


Figure 4.6 Model application process

4.5 Summary

The case study illustrates how the House of Quality is used stepwise, and its result can be used to improve the Energy Performance Certificate in Romania. The first survey had a role in studying the primary needs of the Romanian owner or tenant of a residential building when they retrofit. It was accessed by 233 people with 152 complete and valid answers. The second survey had a role in studying the primary retrofit technologies which can fulfill the needs of the owners and tenants. 36 Accredited Energy Auditor respondents returned the questionnaire, with 25 complete and valid responses. The results of the case study demonstrated that the five most essential retrofit technologies which can contribute to the success of energy efficiency and satisfy the owners at the same time are: (1) application of an external thermal insulation system, (2) replacing the existing windows and doors, (3) roof renovation, (4) replacement of the heating system and air conditioning system and (5) replacement of the water heating system. These points should be highlighted during the development of EPC's recommendation report as they have a higher potential to fulfill the needs valued by the users.

Chapter 5. Conclusions

5.1 Research Summary

The sustainable retrofit process represents a critical action in mitigating the negative impact of the building sector on the environment. However, being a complicated and risky process, the owners have a lack of knowledge about its actions. With this, the Energy Performance Certificate has significant potential to narrow the existent knowledge gap by offering information about the retrofit technologies with the ability to drive stakeholder's motivation to retrofit. However, due to its present format, the EPC is perceived more like a formal requirement than a guiding document containing useful information which can increase sufficiently building owner's awareness of the energy performance of the building or retrofit process. Moreover, the experts emphasize that changes are required to EPC to be used more effectively and to have an actual impact on energy savings. Considering the fact that stakeholder's needs should be considered to boost sustainable retrofit, this study developed a model which analyses the owner and tenant's requirements in a matrix relationship with retrofit technologies through QFD methodology. This attempt made it possible to access the opinion of the stakeholders to find the primary retrofit technologies that can satisfy their demands.

5.2 Contributions

By applying the proposed HoQ model to the case study, the most critical retrofit technologies which satisfy stakeholder's demands and can mitigate the building's impact on the environment were found. Finding the primary methods, to be emphasized, it makes possible to improve the actual recommendation part of the EPC. Through the introduction of these retrofit technologies in the EPC' recommendation report in practice, the Accredited Energy Auditor can give more accurate information to the stakeholders and support their retrofit decision-making. The better the stakeholder's satisfaction, the more successful result will be obtained in energy efficiency using the retrofit process. Moreover, if the application of proposed model last for a long time, the improved stakeholder satisfaction will bring a better reputation to the EPC' recommendation report, meaning increase usage of EPC and significant energy savings. Furthermore, by considering the three pillars of sustainability in its process, this research's findings encourage for the application of sustainability in the construction industry. Consequently, it can be said that this research contributed not just to the body of knowledge but also to help stakeholders to encourage practical retrofit activities.

5.3 Further Research

In this research, the data collection for assessing the development of the model was limited in Romania. Also, the stakeholder's requirements and the retrofit technologies were collected by conducting a literature review. Thus, applying in practice or other case studies, the results can be varied depending on cultural and social background or stakeholder's opinion. Besides this, the study focuses just on residential buildings with owner and tenant as stakeholders. Therefore, the application of the proposed model in the commercial building cases, which have a larger number of stakeholders involved in the decision making, it remained for further studies.

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Appendix A – Stakeholder's Survey Questionnaire

(Adapted English version)

Dear Participant,

On behalf of the Department of Architecture and Architectural Engineering at the Seoul National University, I am pleased to invite you to complete a survey which will be part of a research project and aims to identify the technical methods that have priority in sustainable retrofit projects, with the intention to improve the existent Energy Performance Certificate's recommendation report. To achieve this objective, we are collecting data about the requirements that owners and tenant have while they decide to retrofit. Please be assured that your responses will be kept confidential and will only be used for academic purposes.

Please kindly complete the questionnaire; it will take 3 to 5 minutes. Also, please do not hesitate to contact me if you have any queries regarding the survey questions.

I sincerely thank you for your valuable time!

Sincerely Benzar Bianca Elena,

Graduate student, Department of Architecture and Architectural Engineering, Seoul National University, 08826, Seoul, South Korea; Email:

Part 1. Respondent Background

1. Are you an owner of the propriety or a tenant?
   - ☐ Owner
   - ☐ Tenant

1.1 If you are an owner: Are you an owner of?
   - ☐ Apartment
   - ☐ One family dwelling
   - ☐ Multiple family dwelling

1.2 If you are a tenant: Are you a tenant of?
   - ☐ Apartment
   - ☐ One family dwelling
   - ☐ Multiple family dwelling

Part 2. Building Background

2. Please state in which city is the building located.
   ……………………………………………………………………….

3. Do you possess an Energy Performance Certificate for the apartment /dwelling?
   - ☐ Yes
   - ☐ No
   - ☐ I do not know

3.1 *If yes, please specify which class:*
   - ☐ A
   - ☐ B
   - ☐ C
   - ☐ D
   - ☐ E
   - ☐ F
   - ☐ G
   - ☐ I do not know

4. When was the building build?
   - ☐ Before 1950
   - ☐ 1950-1969
   - ☐ 1970-1989
   - ☐ 1990-2009
   - ☐ 2010-2018

5. When was the building renovated last time?
   - ☐ Never
   - ☐ Less than one year
   - ☐ 1-2 years ago
   - ☐ 3-4 years ago
   - ☐ 5-10 years ago
   - ☐ More than 10 years ago

Part 3. Requirement's importance

Used scale:

- 5 = extremely important
- 4= very important
- 3= somewhat important
- 2= not very important
- 1= not important

6. Considering the environmental concept, please rank in the order of importance the next requirements you have when you decide to retrofit.

☐ Increase energy efficiency
☐ Increase carbon neutrality
☐ Facilitate renewable energy
☐ Meet regulatory requirements
☐ Minimize environmental impact

7. Considering the economic concept, please rank in the order of importance the next requirements you have when you decide to retrofit.

☐ Reduce energy cost
☐ Increase the return of investment
☐ Increase property value
☐ Improve chances for renting
☐ Achieve lower total ownership costs

8. Considering the social concept, please rank in the order of importance the next requirements you have when you decide to retrofit.

☐ Improve occupant's health
☐ Improve occupant's comfort
☐ Improve occupant's productivity
☐ Improve aesthetic quality of the site
☐ The necessity to comply with policy or legislation

Thank you for participating in this research!

Appendix B – Stakeholder's Survey Results

1. Considering the environmental concept, please rank in the order of importance the next requirements you have when you decide to retrofit.

	Owners						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Increase energy efficiency	51	17	14	11	9	102	3.88
Facilitate renewable energy	10	23	13	32	24	102	2.64
Minimize environmental impact	17	24	26	17	18	102	3.05
Increase carbon neutrality	9	13	25	21	34	102	2.43
Meet regulatory requirements	15	25	24	21	17	102	3
	Tenants						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Increase energy efficiency	14	9	13	7	7	50	3.32
Facilitate renewable energy	6	10	5	15	14	50	2.58
Minimize environmental impact	13	10	15	6	6	50	3.36
Increase carbon neutrality	3	12	9	13	13	50	2.58
Meet regulatory requirements	14	9	8	9	10	50	3.16
							Owner + Tenants Score
Increase energy efficiency							3.70
Facilitate renewable energy							2.62
Minimize environmental impact							3.15
Increase carbon neutrality							2.48
Meet regulatory requirements							3.05

2. Considering the economic concept, please rank in the order of importance the next requirements you have when you decide to retrofit

	Owners						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Reduce energy cost	46	23	13	18	2	102	3.91
Increase the return of investment	11	15	25	20	31	102	2.56
Increase property value	13	29	29	25	6	102	3.18
Improve chances for renting	8	12	13	22	47	102	2.14
Achieve lower total ownership costs	24	23	22	17	16	102	3.22
	Tenants						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Reduce energy cost	17	13	8	6	6	50	3.58
Increase the return of investment	4	9	13	13	11	50	2.64
Increase property value	10	9	11	10	10	50	2.98
Improve chances for renting	5	6	13	9	17	50	2.46
Achieve lower total ownership costs	14	13	5	12	6	50	3.34
							Owner + Tenants Score
Reduce energy cost							3.80
Increase the return of investment							2.58
Increase property value							3.11
Improve chances for renting							2.24
Achieve lower total ownership costs							3.25

3. Considering the social concept, please rank in the order of importance the next requirements you have when you decide to retrofit.

	Owners						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Improve occupant's health	53	32	6	6	5	102	4.2
Improve occupant's comfort	20	35	26	13	8	102	3.45
Improve occupant's productivity	3	8	33	28	30	102	2.27
Improve aesthetic quality of the site	11	6	18	30	37	102	2.25
The necessity to comply with policy or legislation	15	21	19	25	22	102	2.82
	Tenants						
Scale Weight	**5**	**4**	**3**	**2**	**1**	**Total**	**Score**
Improve occupant's health	18	10	10	8	4	50	3.6
Improve occupant's comfort	14	16	7	7	6	50	3.5
Improve occupant's productivity	6	5	12	18	9	50	2.62
Improve aesthetic quality of the site	3	7	8	8	24	50	2.14
The necessity to comply with policy or legislation	9	12	13	9	7	50	3.14

	Owner + Tenants Score
Improve occupant's health	4.00
Improve occupant's comfort	3.46
Improve occupant's productivity	2.38
Improve aesthetic quality of the site	2.21
The necessity to comply with policy or legislation	2.92

Appendix C– Accredited Energy Auditor's Survey Questionnaire

(Adapted English version)

Dear Sir / Madame,

On behalf of the Department of Architecture and Architectural Engineering at the Seoul National University, I am pleased to invite you to complete a survey which will be part of a research project and aims to identify the technical methods that have priority in sustainable retrofit projects, with the intention to improve the existent Energy Performance Certificate's recommendation report. Your expertise in the building industry is extremely valuable in assisting me in learning more about the retrofit technologies that have priority in fulfilling owners and tenants' possible requirements while renovating sustainable. Please be assured that your responses will be kept confidential and will only be used for academic purposes.

Please kindly complete the questionnaire in 10 days from now. Also, please do not hesitate to contact me if you have any queries regarding the survey questions. I sincerely thank you for your valuable time!

Sincerely Benzar, Bianca Elena

Graduate student, Department of Architecture and Architectural Engineering, Seoul National University, 08826, Seoul, South Korea; Email:

SECTION A: RESPONDENT'S PROFILE

Please **mark 'x'** in the checkbox to indicate your choice(s) and **fill in** the information where appropriate.

1. Please specify your designation/job title:

   ……………………

2. Please specify your years of experience in the construction industry:

   ☐ Less than 10 years
   ☐ 11 years to 20 years
   ☐ More than 21 years

3. Please specify your years of experience as an Accredited Energy Auditor.

   ☐ Less than 5 years
   ☐ 5 years to 10 years
   ☐ More than 10 years

4. Please specify in what city you work in

   ……………………………..

SECTION B: RELATIONSHIP BETWEEN RETROFIT TECHNOLOGIES AND OWNER/ TENANT'S REQUIREMENTS

This section aims to study the relationship between the retrofit technologies and the demands that the owner and tenants have when they renovate. More accurate, which renovation method has the most significant impact in satisfying what the owner or tenant expect to achieve through renovation.

Please grade, by marking "x" in the boxes given below, the relationship between the technical methods and their potential of fulfilling the below requirements, with consideration of system type (mechanical, electrical and plumbing system, and building envelope).

Note: You can mark just one time per row.

Relationship measure scale:

- No relationship - 0 points
- Low relationship - 1 points
- Medium relationship - 3 points
- High relationship - 9 points

4.1 Mechanical systems retrofit technologies

Replacement of Heating system and Air Conditioning system					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Replacement of Water heating system					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

4.2 Electrical systems retrofit technologies

Lighting fixture					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Replacement of Electrical System					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

4.3 Plumbing system retrofit technologies

Replacement of Domestic hot and cold water system					
	Stakeholders requirements	0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Recycling methods of residual water					
	Stakeholders requirements	0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

4.4 Building envelope retrofit technologies

Applying an external thermal insulation system					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Replacement of windows and doors					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Roof renovation					
Stakeholders requirements		0	1	3	9
Environmental	Increase energy efficiency	☐	☐	☐	☐
	Facilitate renewable energy	☐	☐	☐	☐
	Minimize environmental impact	☐	☐	☐	☐
	Increase carbon neutrality	☐	☐	☐	☐
	Meet regulatory requirements	☐	☐	☐	☐
Economic	Reduce energy cost	☐	☐	☐	☐
	Increase the return of investment	☐	☐	☐	☐
	Increase property value	☐	☐	☐	☐
	Improve chances for renting	☐	☐	☐	☐
	Achieve lower total ownership costs	☐	☐	☐	☐
Social	Improve occupant's health	☐	☐	☐	☐
	Improve occupant's comfort	☐	☐	☐	☐
	Improve occupant's productivity	☐	☐	☐	☐
	Improve aesthetic quality of the site	☐	☐	☐	☐
	The necessity to comply with policy or legislation	☐	☐	☐	☐

Appendix D– Accredited Energy Auditor's Survey Results

1.1 Mechanical systems retrofit technologies

Replacement of Heating ventilation and air conditioning system

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	0	0	8	17	25	7.08
Facilitate renewable energy	1	3	11	10	25	5.04
Minimize environmental impact	1	5	8	11	25	5.12
Increase carbon neutrality	1	8	6	10	25	4.60
Meet regulatory requirements	1	1	14	9	25	4.96
Economic						
Reduce energy cost	0	2	11	12	25	5.72
Increase the return of investment	1	3	12	9	25	4.80
Increase property value	1	3	13	8	25	4.56
Improve chances for renting	0	4	12	9	25	4.84
Achieve lower total ownership costs	0	2	11	12	25	5.72
Social						
Improve occupant's health	1	2	14	8	25	4.64
Improve occupant's comfort	0	1	9	15	25	6.52
Improve occupant's productivity	0	6	12	7	25	4.20
Improve aesthetic quality of the site	4	5	11	5	25	3.32
The necessity to comply with policy or legislation	0	4	12	9	25	4.84

Replacement of Water heating system

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	0	2	10	13	25	5.96
Facilitate renewable energy	2	4	9	10	25	4.84
Minimize environmental impact	1	4	10	10	25	4.96
Increase carbon neutrality	1	8	9	7	25	3.92
Meet regulatory requirements	0	3	13	9	25	4.92
Economic						
Reduce energy cost	0	1	11	13	25	6.04
Increase the return of investment	1	6	8	10	25	4.80
Increase property value	2	4	11	8	25	4.36
Improve chances for renting	0	7	10	8	25	4.36
Achieve lower total ownership costs	0	4	7	14	25	6.04
Social						
Improve occupant's health	4	3	10	8	25	4.20
Improve occupant's comfort	0	5	9	11	25	5.24
Improve occupant's productivity	2	6	12	5	25	3.48
Improve aesthetic quality of the site	7	8	6	4	25	2.48
The necessity to comply with policy or legislation	1	7	10	7	25	4.00

1.2 Electrical systems retrofit technologies

Lighting fixture

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	1	3	9	12	25	5.52
Facilitate renewable energy	1	4	17	3	25	3.28
Minimize environmental impact	0	7	10	8	25	4.36
Increase carbon neutrality	3	9	7	6	25	3.36
Meet regulatory requirements	1	5	13	6	25	3.92
Economic						
Reduce energy cost	0	3	6	16	25	6.60
Increase the return of investment	2	8	8	7	25	3.80
Increase property value	3	9	8	5	25	3.12
Improve chances for renting	1	9	8	7	25	3.84
Achieve lower total ownership costs	1	6	9	9	25	4.56
Social						
Improve occupant's health	3	7	7	8	25	4.00
Improve occupant's comfort	0	7	9	9	25	4.60
Improve occupant's productivity	0	8	9	8	25	4.28
Improve aesthetic quality of the site	4	7	9	5	25	3.16
The necessity to comply with policy or legislation	0	8	9	8	25	4.28

Replacement of Electrical System

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	3	7	8	7	25	3.76
Facilitate renewable energy	3	5	11	6	25	3.68
Minimize environmental impact	5	7	8	5	25	3.04
Increase carbon neutrality	5	7	8	5	25	3.04
Meet regulatory requirements	1	9	10	5	25	3.36
Reduce energy cost	2	7	7	9	25	4.36
Increase the return of investment	4	11	5	5	25	2.84
Increase property value	1	9	8	7	25	3.84
Improve chances for renting	0	8	10	7	25	4.04
Achieve lower total ownership costs	3	8	6	8	25	3.92
Improve occupant's health	4	7	8	6	25	3.40
Improve occupant's comfort	1	8	7	9	25	4.40
Improve occupant's productivity	2	8	10	5	25	3.32
Improve aesthetic quality of the site	5	8	9	3	25	2.48
The necessity to comply with policy or legislation	1	5	10	9	25	4.64

1.3 Plumbing system retrofit technologies

Replacement of Domestic hot and cold-water system

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	1	2	11	11	25	5.36
Facilitate renewable energy	2	7	10	6	25	3.64
Minimize environmental impact	2	5	13	5	25	3.56
Increase carbon neutrality	2	7	11	5	25	3.40
Meet regulatory requirements	2	4	11	8	25	4.36
Economic						
Reduce energy cost	1	2	9	13	25	5.84
Increase the return of investment	2	8	9	6	25	3.56
Increase property value	1	8	8	8	25	4.16
Improve chances for renting	0	10	8	7	25	3.88
Achieve lower total ownership costs	1	4	9	11	25	5.20
Social						
Improve occupant's health	1	4	11	9	25	4.72
Improve occupant's comfort	0	7	6	12	25	5.32
Improve occupant's productivity	2	8	9	6	25	3.56
Improve aesthetic quality of the site	7	5	9	4	25	2.72
The necessity to comply with policy or legislation	3	5	9	8	25	4.16

Recycling methods of residual water

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	4	6	10	5	25	3.24
Facilitate renewable energy	5	8	8	4	25	2.72
Minimize environmental impact	2	6	10	7	25	3.96
Increase carbon neutrality	4	8	10	3	25	2.60
Meet regulatory requirements	2	5	12	6	25	3.80
Economic						
Reduce energy cost	3	8	7	7	25	3.68
Increase the return of investment	3	10	9	3	25	2.56
Increase property value	2	9	9	5	25	3.24
Improve chances for renting	2	10	9	4	25	2.92
Achieve lower total ownership costs	2	9	7	7	25	3.72
Social						
Improve occupant's health	3	6	13	3	25	2.88
Improve occupant's comfort	3	12	6	4	25	2.64
Improve occupant's productivity	5	12	6	2	25	1.92
Improve aesthetic quality of the site	7	11	4	3	25	2.00
The necessity to comply with policy or legislation	3	4	12	6	25	3.76

1.4 Building envelope retrofit technologies

Applying an external thermal insulation system

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	0	0	1	24	25	8.76
Facilitate renewable energy	2	8	7	8	25	4.04
Minimize environmental impact	0	4	8	13	25	5.80
Increase carbon neutrality	1	3	6	15	25	6.24
Meet regulatory requirements	0	1	10	14	25	6.28
Economic						
Reduce energy cost	0	1	1	23	25	8.44
Increase the return of investment	1	4	6	14	25	5.92
Increase property value	0	0	8	17	25	7.08
Improve chances for renting	0	0	8	17	25	7.08
Achieve lower total ownership costs	0	2	5	18	25	7.16
Social						
Improve occupant's health	2	3	10	10	25	4.92
Improve occupant's comfort	1	1	3	20	25	7.60
Improve occupant's productivity	1	4	9	11	25	5.20
Improve aesthetic quality of the site	2	2	7	14	25	5.96
The necessity to comply with policy or legislation	0	1	8	16	25	6.76

Replacement of windows and doors

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	0	0	3	22	25	8.28
Facilitate renewable energy	2	6	11	6	25	3.72
Minimize environmental impact	0	4	10	11	25	5.32
Increase carbon neutrality	2	2	5	16	25	6.44
Meet regulatory requirements	0	2	9	14	25	6.20
Economic						
Reduce energy cost	0	1	1	23	25	8.44
Increase the return of investment	2	4	7	12	25	5.32
Increase property value	0	0	9	16	25	6.84
Improve chances for renting	0	2	6	17	25	6.92
Achieve lower total ownership costs	0	2	4	19	25	7.40
Social						
Improve occupant's health	3	1	8	13	25	5.68
Improve occupant's comfort	1	1	5	18	25	7.12
Improve occupant's productivity	1	3	10	11	25	5.28
Improve aesthetic quality of the site	1	2	5	17	25	6.80
The necessity to comply with policy or legislation	0	1	10	14	25	6.28

Roof renovation

Stakeholders requirements	0	1	3	9	Total	Weighted Average
Environmental						
Increase energy efficiency	0	1	3	21	25	7.96
Facilitate renewable energy	0	2	13	10	25	5.24
Minimize environmental impact	1	7	6	11	25	4.96
Increase carbon neutrality	1	5	9	10	25	4.88
Meet regulatory requirements	3	7	7	8	25	4.00
Economic						
Reduce energy cost	0	2	2	21	25	7.88
Increase the return of investment	0	3	8	14	25	6.12
Increase property value	1	1	11	12	25	5.68
Improve chances for renting	2	5	6	12	25	5.24
Achieve lower total ownership costs	0	1	15	9	25	5.08
Social						
Improve occupant's health	0	1	9	15	25	6.52
Improve occupant's comfort	2	2	5	16	25	6.44
Improve occupant's productivity	2	2	6	15	25	6.20
Improve aesthetic quality of the site	3	3	11	8	25	4.32
The necessity to comply with policy or legislation	2	7	10	6	25	3.64