DEVELOPMENT OF AN ANALYTIC METHOD FOR ASSESSING THE PERFORMANCE OF RETROFITS FOR COMMERCIAL BUILDINGS

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Development of An Analytic Method for Assessing The Performance of Retrofits for Commercial Buildings

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Abstract of thesis entitled : Development of an analytic method for assessing the performance of retrofits for commercial buildings

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Facility management (FM) embraces multiple disciplines of practice to ensure the functionality, comfort, safety, and the efficiency of the built environment by integrating people, place, process, and technology. During the FM stage of a building, the building's facilities inevitably deteriorate. By implementing building retrofits, the performance of the facilities and hence the work environment of the building can be significantly improved. Many studies have been undertaken to help building owners and facilities managers make decisions on building retrofit projects. But there is still limited research on developing an analytic method for evaluating the holistic performance of commercial building retrofits. To address this research gap, a study was initiated.

This study, consisting of four stages, aims to develop a credible assessment method for evaluating building retrofit in commercial buildings and validate the applicability of the assessment method so developed. Through a systematic literature review in Stage 1 of the study, a total of 52 performance indicators were identified as applicable to assessing the performance of building retrofits. After consolidation and refinement, the indicators were

grouped into four aspects, namely, environmental, economic, health and safety, and users' perspective. In Stage 2, a focus group study was conducted with participation from FM experts, resulting in a preliminary shortlist of 19 key performance indicators (KPIs) for assessing building retrofits performance.

In Stage 3, an industry-wide online survey was conducted to solicit the opinions of building practitioners on the importance levels of the 19 KPIs. Eight KPIs were finally shortlisted, which are: energy savings (%), payback period (year), investment cost ($), ratio of actual to target number of statutory orders removed (%), ratio of actual to target number of accidents reduced (%), target indoor air temperature (^{o}C), target indoor air quality (IAQ) class, and target workplane illuminance (lux). In general, agreement on the rankings of the KPIs was reached among the industry participants, despite their differences in gender, academic qualification, and job level.

In Stage 4, 12 in-depth interviews were conducted to find out the relative importance weights of the eight selected KPIs using the Analytic Network Process (ANP). The applicability of the developed assessment method was then validated with individual sets of importance weights for the KPIs and empirical building data of ten case studies.

Each of the case studies had unique building characteristics (age of buildings ranged from 5 to 44 years; no. of storeys ranged from 6 to 39; total gross floor areas of the buildings ranged from 2,800m^2 to 115293m^2; and retrofit project costs varied from $0.63M to $81M). Self-evaluations were conducted by the interviewed FM professionals, where they indicated the levels of expectation fulfilment of the retrofit projects. The results show that the established analytic assessment method is feasible and useful for evaluating the performance of building retrofits for real-world commercial buildings.

PUBLICATIONS ARISING FROM THIS THESIS

Ho, A. & Lai, J. 2018. Building retrofit: review on modelling studies, real applications and barriers, *The 9th Great Pearl River Delta and 2nd Guangdong, Hong Kong and Macao Dawan District Building Operation and Maintenance Conference Proceedings*, Guangzhou, 15 December, pp. 54-61.

Ho, A.M.Y., Lai, J.H.K. & Chiu, B.W.Y., 2021. Key performance indicators for holistic evaluation of building retrofits: Systematic literature review and focus group study. Journal of Building Engineering, 43, p.102926.

Ho, A., Lai, J. & Chiu, B. 2021. Shortlisting KPIs for holistic performance evaluation of commercial building retrofits, *CIBSE Technical Symposium*, UK 13-14 July 2021.

Ho, M.Y., Lai, J., Hou, H., & Zhang, D. (2021). Key Performance Indicators for Evaluation of Commercial Building Retrofits: Shortlisting via an Industry Survey. Energies (Basel), 14(21), 7327.

Ho, A., Lai, J. & Hou, H. Assessing the performance of commercial building retrofits: An analytic network process model (full draft prepared).

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AHP	– Analytic hierarchy process
ANP	– Analytic network process
BEAM	– Building Environmental Assessment Method
BEAM Plus	– Building Environmental Assessment Method Plus
BIM	– Building Information Modelling
BREEAM	– Building Research Establishment Environmental Assessment Method
BSOMES	– Building Services Operation and Maintenance Executives Society
BPE	– Building Performance Evaluation
CIBSE	– Chartered Institution of Building Services Engineers
DOE	– Department of Energy
ECMs	– Energy Conservation Measures
EEMS	– Energy Efficient Measures
ERMs	– Energy Retrofit Measures
EUI	– Energy use index
FM	– Facilities (UK) / Facility (US) Management
GFA	– Gross floor area
HKIE	– Hong Kong Institution of Engineers
HKIFM	– Hong Kong Institution of Facility Management
HVAC	– Heating, ventilation and air-conditioning system
IAQ	– Indoor air quality
IEQ	– Indoor environmental quality
IFA	– Internal floor area

IFMA	– International Facility Management Association
LCC	– Life cycle cost
KPI	– Key performance indicator
LEED	– Leadership in Energy and Environmental Design
NPV	– Net present value
OC	– Owners' Corporation
O&M	– Operation and maintenance
PB	– Payback period
PV	– Photovoltaic
ROI	– Return on investment
RII	– Relative importance index

Chapter 1 Introduction

1.1 Background

Facility management (FM) includes multiple disciplines of practice to ensure the functionality, comfort, safety, and the efficiency of the built environment by integrating people, place, process, and technology. Through building retrofits, the working environment and the performance of facilities can be significantly improved. FM practitioners are responsible to communicate with the retrofitting decision makers and facility users, modify the facilities and upgrade the systems for energy use, and develop mechanisms for energy consumption measurement, energy using process monitoring and energy performance assessment (Escrivá-Escrivá, 2011; Mawed *et al.*, 2020). Thus, FM practitioners play a critical role in supporting decision making on building retrofitting, and their opinions on KPIs for building retrofitting performance are useful.

1.1.1 What are retrofits?

Building retrofitting is a form of technical intrusion in the systems or structure of a building after its initial construction and occupation (Shaikh *et al.*, 2017). This practice can improve the building performance to optimize energy utilization and increase building users' occupation experience. In recent years, building retrofitting also included green retrofitting or sustainable retrofitting, which is used to emphasize the environmental benefits of retrofitting work in the built environment.

US Green Building Council (USGBC) defines green retrofitting as "*… any upgrade of an existing facility to improve energy and environmental performance, decrease usage of* *water and enhance existing comfort and quality of interior spaces – all achieved in a manner that provides financial incentives to the investor*" (Jagarajan *et al*., 2017).

The definition of Deep Energy Retrofit (DER) from the IEA-EBC Annex 61 is "*a major building renovation project in which site energy use intensity (including plug loads) has been reduced by at least 50% from the pre-renovation baseline with a corresponding improvement in indoor environmental quality and comfort.*" (Zhivov *et al*., 2015).

Common building retrofitting projects include energy efficiency retrofits, water efficiency retrofits, HVAC commissioning, green roof establishment, ventilation system retrofits, operations and maintenance optimization, space utilization and reconfiguration, etc. Three levels of energy efficiency building retrofits in Kuwait were discussed by Krarti (2015):

- Level-1 retrofit are buildings undergoing basic energy audit followed by carrying out low-cost energy efficiency measures, for example, installation of programmable thermostat, use of LED lighting, which can save eight percent for all building types.
- Level-2 retrofit includes improved building envelope components, energy efficient cooling systems and appliances, which can achieve an average of 23% in energy saving.
- Level-3 retrofit includes deep retrofit such as window replacement, cooling system replacement, use of variable speed drives and installation of daylighting control systems.

Instead of a standalone system of the above measures, DER (level-3) adopts a whole-building analysis approach and an integrative design process, where the building is considered a single integrated system (Zhivov and Lohse, 2020). At least 80% of the building energy performance can be improved if the deep retrofit follows the most recent and proposed European Union guidance (RICS 2013). From the case studies in the Middle East and North Africa region, the energy savings were up to 32% (Krarti and Ihm, 2016).

1.1.2 Why needs retrofits?

A global survey from 400 occupiers reported that 69% of corporate real estate executives thought that sustainability was an important business issue. More than one-third (40%) of participants rated energy and sustainability was a "major factor" and willing to pay a premium of 1-5% to lease green space (42%). (Arup, 2009).

There were at least 35 benefits arising from building retrofit, which can be summarized in various aspects, namely environmental, health and community, financial, market and industry benefits (Durmus-Pedini and Ashuri, 2010) (Figure 1). Two of the key objectives in designing sustainable buildings were to lower the operational energy consumption of buildings and reduce their life-cycle costs (Morrissey *et al*., 2014, Wolf, 2011). Other co-benefits from retrofits include less global warming and pollution, easier to sell or let the building at a higher price (Morrissey *et al*., 2014; Thomas, 2010), better indoor environment, better utilization of the floor area, etc. which they are often more valuable than the energy savings (Thomas, 2010).

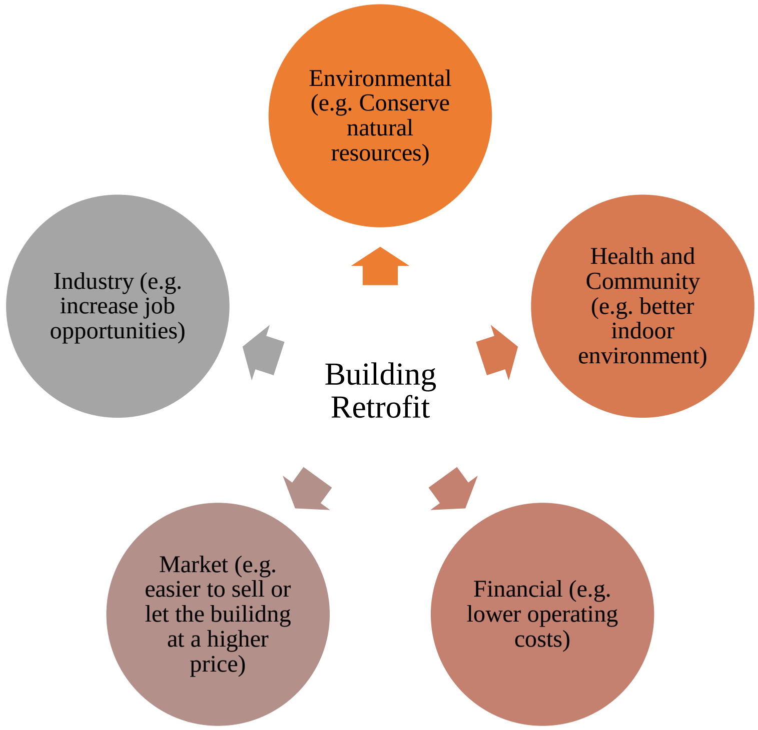

Figure 1.1 The benefits of building retrofit (Durmus-Pedini and Ashuri, 2010)

1.2 Different aspects of building retrofits

FM performance can be evaluated by as many as 172 key performance indicators (KPIs), which can be grouped into eight categories, namely business benefits, equipment, space, environment, change, maintenance or service, consultancy and general (Hinks and McNay, 1999). Retrofit performance evaluation indicators can be categorized into four aspects, namely economic, environmental, health and safety and users' perspective (Ho *et al*., 2021). To study the FM performance of a teaching hotel, the relative important weights of KPIs including energy consumption (per unit area per month), operation and maintenance cost within budget, facilities condition, customer expectation and number of equipment failure were found by using analytic hierarchy process (AHP) (Lai and Choi, 2015).

A state-of-the-art review on selection and identification of the best retrofit options for existing buildings was conducted (Ma *et. al*., 2012), which covered key issues including energy auditing, building performance assessment, quantification of energy benefits, economic analysis, risk assessment and measurement and verification of energy savings of retrofit projects. Another review on retrofit strategies was made (Asadi *et al*., 2013), which examined the research and development in the decision support processes in building retrofits. Other review studies include the work of Liu *et al*. (2020), which focused on policy instruments for green retrofits for existing buildings; and the study of Kylili *et al.* (2016), where the KPIs approach to building renovation was presented and eight generic categories of building performance were identified, viz. economic, environmental, social, technological, time, quality, disputes and project administration. To help building owners and facilities managers make decisions on building retrofits, a significant volume of studies has been undertaken (Caccavelli and Gugerli, 2002; Albatici *et al*., 2016).

As sustainability is one of the key project goals, an increasing volume of studies in the literature have examined KPIs for measuring the level of sustainability in construction and building renovation/retrofit projects. Kylili *et al*. (2016) provided a state-of-the-art review on the KPIs identified for measuring the sustainability of the projects in the built environment, in which they categorised the building performance KPIs into eight groups—namely, economic, environmental, social, technical, time, quality, disputes, and project administration. Al Dakheel *et al*. (2020) conducted a review on features of smart buildings (SBs) and identified 10 KPIs for SBs. The KPIs they identified help to quantify the 'smart features' of SBs and reflect the 'smart capability' of the building. The validity of KPIs affects the overall measurement results; thus, the selection process of KPIs should engage scientific methodologies to ensure their representativeness of the measurement goals (Collins *et al*., 2016).

In the past decade, a considerable number of studies have been conducted in evaluating the performance of building renovation.

- Energy aspect: normalized annual energy consumption; energy use for heating (kWh/m^2); annual electricity use (kWh/m^2); energy and time consumption index; energy savings due to retrofit (kWh/year) (Antines *et al*., 2013); greenhouse gas emission (Nielsen *et al*., 2016); normalized annual total carbon emission of buildings (Lai and Lu, 2019).
- Financial aspect: cost of conserved energy; internal rate of return of the energy investment; annual ongoing maintenance charges; cost of retrofit; direct costs and initial investment cost (Antines *et al*., 2013); existing rent income, cost for repair (Nielsen *et al*., 2016); payback time (Zanchini *et al*., 2015). In practice, payback period has two alternatives in use, namely the static and dynamic payback period (Curmei-Semenescu, 2019). The static payback period does not consider an opportunity cost of money and basically estimates the period needed for the sum of cash flow generated by the investment equal to its initial cost. This method is simple to compute and easy to understand by the investors. The dynamic payback period uses the discounted cash flows at the moment of the initial investment, result in higher values than the static payback period and allow comparison between projects with different risk.

- Global environment: reduction potential of global warming emissions; water use.
- The indoor environmental quality and comfort: thermal comfort indices (predicated mean vote, predicated percentage of dissatisfaction); discomfort hours during summer or winter (Antines *et al*., 2013); expected quality of living before and after renovation (Nielsen *et al*., 2016).

1.2.1 Economic

In European Union energy policies, there was a concept of cost optimality and target to nearly zero-energy (low energy consumption). According to the European Energy Performance Building Directive definition, a nearly zero-energy building is "a building that has a very high performance" (The Energy Performance of Buildings Directive, 2010). To achieve nearly zero-energy building (Ferrari and Beccali, 2017) with lowest cost, it was crucial to apply renewables. By using PV panels to generate an equal amount of non-renewable energy for primary use, the hierarchy of cost effectiveness can be kept (Ferreira *et al*., 2014). The cost of revocability (e.g. energy costs reduction due to installation of passive systems) can be as high as 27% in retrofit buildings (Tokede *et al*., 2018).

The investment in the sustainability of commercial buildings on average was economically viable (Kok *et al*., 2012). An energy retrofit project of a typical Italian commercial building built in 1998 resulted in a saving of € 143,000 due to tax credit mechanism over ten fiscal years, with reduction of 40% of the primary energy consumption by intervention just on the envelope (Alajmi, 2012). A simulation result of a reference office building can achieve about 42.4 dollars/m^2 in global cost savings and highly reduce the energy consumption, discomfort hours and polluting emissions (Ascione *et al*., 2017). Other indirect benefits brought by retrofits include stipulation of a single contract with an energy company to sell the energy produced by photovoltaic panels, new spaces for personal services, condominium car sharing service and a new building ultra-speed Wi-Fi network (Mecca *et al*., 2020). As such, a global survey revealed that more than half (53%) of participants would pay a premium to renovate property for acquire sustainability benefits (Arup, 2009).

In other studies, economic feasibility for the refurbishment of buildings was evaluated (Napoli *et al*, 2020; Ruparathna *et al*, 2017). When considering the payback period, energy cost savings alone could be very long for retrofit projects that were not planned for other reasons (such as tenant improvements, HVAC component replacement at the end of useful life, or market repositioning by new owners). However, the payback from total benefits, such as green branding, occupant productivity, and lower vacancy rates can easily be under 5 years (Nock and Wheelock, 2010). For deep energy retrofit (DER), information regarding the reduction in investment cost, planning cost, operating cost and quality assurance were discussed (Zhivov and Lohse, 2021). Investment costs can be reduced by an additional 5-10% by sizing all equipment and execution of DER project in one phase instead of several consecutive steps. For energy cost savings, increase in usable floor space by about 10% can give an additional 20-50%. Also, using renewable energy technologies eligible for subsides or rebates with DER can improve overall project cost-effectiveness by another 30-50% of energy cost savings. Other cost benefits such as direct and indirect cost savings were summarized below (Table 1.1):

Table 1.1 Direct and indirect cost savings beyond energy cost savings due to DER (Summarized and extracted from Zhivov and Lohse, 2021)

Benefits	Increase in %
Maintenance costs (Fowler *et al*., 2008; Leonardo Academy, 2008)	-(9.0–14)%
Occupational satisfaction (GSA, 2011)	+(27–76)%
Rental premium (Eicholtz and Quigley, 2010)	+(2.1–17)%
Property sale price premium (Eicholtz and Quigley, 2010)	+(11.1–26)%

1.2.2 Environmental

Building retrofits are critical to improve energy performance and sustainability (Lee *et al*.,2019). Retaining as much of the structure as possible and upgrade and optimize systems can result in minimal environmental impact (Abul, 2016). The example of the "1315 Peachtree Street" commercial building showed that after retrofitting, it complied with the LEED Platinum requirement and achieved 68 % of carbon footprint reduction (Abul, 2016). The retrofitting case study of the China Resources Building (CRB) in Hong Kong also showed that the implemented sustainable retrofit strategies successfully mitigated the impact of climate change on building energy use for almost 40 years (Wan *et al*., 2015). With on-site renewable energy sources and an integrated retrofit strategy of prefabricated retrofit module, total energy needs of a single-family retrofitted building highly reduced by 83% (Silva *et al*., 2013a). Through primary energy audit (including using building construction studies, questionnaires, examination of the energy consumption strategies and energy simulation), there were significant energy savings in two public sector office buildings in northern Greece. Cooling demand due to proper shading and natural ventilation decreased significantly by 63% and 53% in the Thessaloniki building, and 81%

and 43% in Kozani building respectively (Koinakis and Sakelaris, 2008). Retrofitted through optimal combinations of energy efficient measures (EEMs) and rooftop integrated photovoltaics indicated a potential primary energy savings of 54% (i.e., 8000 GWh) (Luddeni *et al*., 2018). A reduction of 957GWh annual electricity consumption, 214MW in peak demand and over 660k-ton per year in carbon emissions were resulted from a basic large-scale energy efficiency retrofit program (Krarti and Dubey, 2017). It was possible to reduce primary energy demand and associated emissions up to 40% from the current values by adopting market-available and well-proven technological solutions for retrofit (Ferrari and Beccali, 2017).

Energy saving is an important parameter in building retrofit performance evaluation. According to Deb and Lee (2018), the best set of variables in exploring energy saving potential of office buildings consists of i) gross floor area (GFA), ii) non-air-conditioning energy consumption, 3.) average chiller plant efficiency, and 4.) installed capacity of chillers. For the energy-saving based project (energy saving is the project prime concern), study from Filippi *et al.* (2020) showed that doubling the current investments can result in 60% reduction in baseline energy consumption while over three times of the current investment can allow maximum energy saving of 75%.

The building energy performance assessment methods using simulation method and statistical models, details of classification of energy assessment were discussed (Seyedzadeh, 2021). The “Green Energy Audit” (GEA) procedure, it aims to evaluate the degree of improvement in sustainability of the building where the choices do not necessarily generate benefit in terms of energy saving, but also including advantages as regard to sustainability (Dall'O' *et al*., 2020). For energy performance certificate scheme adopted in the UK (Healy, 2011), the relationship between different energy certificate types for UK buildings were studied. The operating energy performance can be displayed in terms of seven letter ranks from A (the lowest number, the best) to G (the worst). On the other hand, "Wastewi$e Certificate", "Energywi$e Certificate", "IAQwi$e Certificate" and "Carbon Reduction Certificate" were established in Hong Kong in 2020 to encourage companies to adopt measures to save energy, reduce the amount of waste generated, improve indoor air quality and recognize their efforts in environmental protection through carbon reduction. By fulfilling the certificate requirement (measured in three levels for energy, waste and IAQ: "basic", "good" and "excellent". "% of reduction": for carbon reduction certificate), it helps increase business competitiveness by attracting those customers who value companies that are committed to improve environmental quality as well as to enhance corporate image (Environmental Campaign Committee and Environmental Protection Department, 2021a;b;c;d).

1.2.3 Health and safety

Human health, safety and well-being are one of the key issues for a retrofit project. Sick building syndrome is the common denomination for buildings with defects or functionality that people need to face health issues. Defects found in buildings can affect the functionality of building and lower the performance of occupants. Common building defects can occur in various forms and all types of buildings irrespective of age such as defective concrete, spalling or loose plaster in ceilings, water seepage from external wall/window/roof/ceiling, structural cracks in walls/column/beams and defective wall finishes/tiles. For a more serious defect that defective concrete is extensive and penetrates to the steel bars, building retrofit or even demolition is required (Buildings Department, 2002).

In addition, some old commercial premises are basically found to have inadequate fire service installations that may pose danger to the occupiers when there is a fire. Upgrading and improvement of fire service installations (e.g. adding sprinkler system, reinstatement or improvement of smoke lobby doors, fire resisting construction such as walls and openings etc.) is essential for occupants' safety through retrofitting (Buildings Department, 2002). Proper design, operation and maintenance of building facilities help prevent the spread of legionella and diseases from cooling towers (Electrical and Mechanical Services Department, 2019). To evaluate whether the engineering facilities performance is complied with relevant legal requirement or not, health, safety and legal performance indicators can be used to reflect the consequences of poor facilities' performance (Lai and Man, 2017). It can show how well the operation and maintenance team perform in safeguarding the health and safety of occupants and prevent any disruption (e.g. power outage leading to business loss) (Lai and Man, 2018a, Lai and Man, 2018b). These indicators are useful to practitioners such as tactical level as well as senior management at the strategic level.

1.2.4 Users' perspective

Comfortable indoor environment plays an important role for the occupants, and can be classified into thermal comfort (temperature, humidity and air circulation), olfactory comfort (smell and breathing), acoustic comfort (noise), visual comfort (slight and color effects) and special factors (e.g. solar inputs, ionization, vibration and movements of the building, etc.) (Felseghi *et al*., 2019). Thermal comfort was perceived as the most important by the residents out of the four key IEQ attributes namely air cleanliness, odor, and noise (Lai and Yik, 2009).

Renovating older buildings could be greener than destroying them and rebuilt. The green practices helped increase energy efficiency, optimize building performance, increase tenants' satisfaction and boost economic return while reducing greenhouse gas emission from the studies conducted for buildings in USA, Taipei, UK and Korea (Al-Kodmany, 2014). With 12.9% (8.6% net) increase in rents, occupants can receive a better indoor climate, including improved temperature conditions during winter regarding to low temperature, draught and cold areas in the flat, improvement in air quality such as mold growth, and less noise from outside (Thomsen *et al*., 2016). By implementing the retrofitting measures of the HVAC system viz. a sensor-based building management system, dehumidification of outdoor air, and a two-stage particle filtration system, half of the energy use was reduced while the indoor thermal comfort can be maintained at an acceptable level. The outdoor particulate matter ingress was reduced by 30% to 60% more than the aluminum filter used before the retrofit. At most of the time, the indoor particle levels complied with the World Health Organization's guidelines. (Che *et al*., 2019). A better indoor environmental condition in the workplace, health and job satisfaction were core factors of productivity for employees. By moving to the green and healthy building, the prevalence of sick leave can be reduced by 2% and significantly enhance job satisfaction (Palacios *et al*., 2020).

1.3 Research gap

The research topics on operation and maintenances mainly covered five areas, including (i) innovation of new technologies and energy auditing, (ii) life cycle cost assessment and certification rating system, (iii) comprehensive risk analysis and integrated retrofit process, (iv) benchmarking and evaluation and (v) effect of occupant behavior. In the study of Shanshan *et al.* (2015), the existing building retrofitting process was reviewed, including the functional, technical, and organizational issues of the green retrofit design (GRD) process. It was found that environmental, social, and technical issues were often examined separately in the decision process.

Although many research studies have already existed on technology, energy audit, simulation modelling, life cycle cost analysis etc., deviations were found between simulation results and actual performance of retrofit works. Investigations into individual aspects (e.g., energy, cost) of retrofit measures, have also been widely conducted; but there has been limited research that aims to develop an analytical method for evaluating the holistic performance of building retrofits (Mantha *et al*., 2018; Gonzalez-Caceres *et al*., 2019; Liu *et al*., 2018; Rocchi *et al.*, 2018; Ruparathna *et al*., 2017). Many previous studies focused mainly on assessing the retrofits performance in different aspects separately. Yet, there is limited holistic performance evaluation method for building retrofit.

To help building owners and facilities managers make decisions on building retrofits, it is essential to identify indicators for developing an analytic method for evaluating the holistic performance of building retrofits. To address the above research gap, a study was initiated with a mixed methods approach combining positivism and interpretivism. Forming the fundamental part of this study, an extensive desktop research was carried out to search and identify literature germane to the study. From such literature, indicators applicable for reflecting the performance of building retrofits were identified and used for developing an analytic assessment method through quantitative (industry-wide survey) and qualitative (a focus group study and a series of interviews) approach. Therefore, a rigorous retrofit performance evaluation can serve as a real application example and guideline to encourage more decision-makers to carry out retrofit projects.

As policy instruments for green retrofit in existing buildings including providing a series of means to grade energy performance of existing buildings (Liu *et al*., 2020), this study also helps improve the rate of green retrofit in existing buildings through encouraging the building energy consumption disclosure and experience dissemination, performance evaluation of existing buildings. Case studies will also be conducted in this research to validate the developed method and presenting more information of the actual building evaluation.

1.4 Research questions

The research intended to answer the following questions:

(i) What are the methods available for assessing building retrofits?

(ii) Are there indicators used in the methods for assessing building retrofits and, if so, what are they?

(iii) Among the above indicators, which of them are key performance indicators (KPIs) that should be used for developing an analytic method for assessing the performance of building retrofits?

(iv) How to shortlist the KPIs and how to develop the assessment method?

(v) Is the method developed valid and applicable to retrofits for real-world commercial buildings?

1.5 Research objectives

This research objective is to develop an assessment method for evaluating building retrofit in commercial buildings with the following objectives:

(i) To identify indicators applicable to measuring the performance of retrofit projects for commercial buildings;

(ii) To shortlist the identified indicators to become key performance indicators (KPIs) for use in assessing building retrofit performance;

(iii) To determine importance weights of each of the KPIs;

(iv) To develop a credible assessment method based on the KPIs, for evaluating building retrofit performance for commercial buildings; and

(v) To validate the applicability of the developed assessment method.

1.6 Research significance

To develop a comprehensive retrofit assessment method for commercial buildings, this study helps improve the existing theoretical frameworks for building retrofit evaluation (Figure 1.2). The applicability and feasibility KPIs were identified through a series of rigorous studies. Through application of analytical network process, an assessment method for evaluating building retrofit in commercial buildings was developed and revealed the priority of these KPIs. This developed method was also applicable to the real commercial buildings, and help building owners and facilities managers to make decisions on building retrofits.

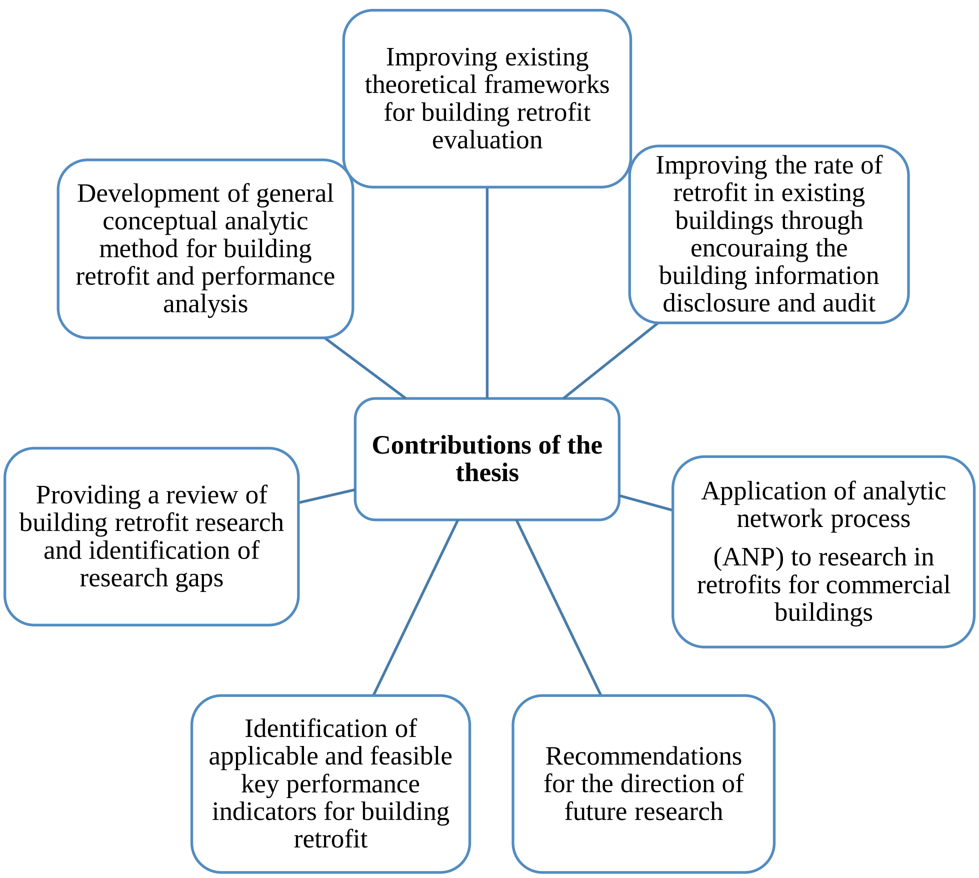

Figure 1.2 Theoretical and practical contribution of this Ph.D thesis

1.7 Outline of the thesis

This thesis comprises eight chapters. Chapter 1 introduces the background information of building retrofit and the research gap of individual performance evaluation in retrofit project is revealed. Then, research questions are formulated and the main objectives and initiative of conducting the study are discussed. Finally, the study's significance and overview of the thesis is given.

Chapter 2 first reviews the background information of commercial buildings in Hong Kong. The common retrofit strategies are also presented. This chapter also focuses on how the retrofit projects are evaluated, including classification of building types, adopted retrofit measures, investigation focus, data collection methods and the evaluation approaches. Lastly, this chapter presents the performance indicators of various aspects (economic, environmental, health and safety and users' perspective) in evaluating the building retrofit performance. Grouping and consolidation helps eliminate the duplicated KPIs and gain a preliminary understanding of how retrofits can applicable to measuring the performance of retrofit projects for buildings.

Chapter 3 introduces the research methodology and process, which involves the flow of the study, the analytical framework, and choices. There are four stages in this study. Stage 1-3 (literature reviews, focus group meeting and survey) allow identifying and shortlisting of KPIs for retrofit performance evaluation. At Stage 4 (method development and validation), carrying out in-depth interviews allows data collection and analyzing the actual performance of retrofit projects. This chapter also explores the application of analytic network process (ANP) for assessing the performance of retrofits.

Chapter 4 presents the primary screening of KPIs and findings in focus group study. This chapter also offers and discusses the feasibility and applicability of KPIs, including the new suggested indicators by the FM professionals. Chapter 5 further studies the importance level of KPIs through secondary screening via an industry-wide online surveys. This chapter also investigates the perception of KPIs by different parties. The shortlisted KPIs can form the cornerstone for further development of an analytic evaluation scheme for assessing the performance of retrofits for commercial buildings.

Chapter 6 discusses the inter-relationship of KPIs and the establishment of the KPIs network model by analytic network process (ANP). The calculation methods and process of in-depth interviews are also presented to find out the relative importance weights of KPIs. Chapter 7 presents ten cases studies for method validation. The details and findings from the interviews are summarized. By the use of the relative importance weights from ANP and professional judgement of interviewees, it helps explore and prove the applicability of the developed analytic method for assessing the performance of retrofits for commercial buildings.

Chapter 8 concludes the major findings, areas of improvement and recommendations for future study. It summarizes the theoretical and practical issues that emerge from this research.

Chapter 2 Literature Review

2.1 Introduction

The previous chapter briefly introduces the summary of relevant publications on retrofit performance evaluation and reveals the research gap. In this chapter, another extensive literature review was further conducted. The background information of commercial buildings, common retrofit strategies, and possible performance indicators for assessing building retrofit are introduced. The identification process of performance indicators and their definitions are explained in detail. In addition, this chapter also provides findings from literatures, including their investigation focus, applied retrofit measures, data collection methods and evaluation methods for building retrofits.

2.2 Background of commercial building in Hong Kong

2.2.1 Commercial buildings in Hong Kong

Hong Kong, a crowded city with hilly terrain, has a total land area of 1,104 km^2, while only 263 km^2 are for living and working (Environment Bureau *et al*., 2015). In Hong Kong, the private office premises are buildings designed for commercial or business purposes, excluding non-domestic floors in composite buildings. At the end of 2018, the total stocks of private offices accounted for 12,053,300 m^2, consisting of 65 % Grade A, 23% Grade B and 12% Grade C buildings (Rating and Valuation Department, 2019).

The Hong Kong Property Review classified offices into Grades A to C, which correspond to the building quality - from high to low, respectively. For private commercial premises, they also include retail and other premises designed for commercial use, with exception of the purpose-built offices, car parking space and those owned by the Housing Authority and Housing Society (Rating and Valuation Department, 2019). The grading definitions are as shown in Tables 2.1 and Table 2.2 (Rating and Valuation Department, 2019):

Table 2.1 Grading definition for commercial buildings in Hong Kong

Grade	Finishes	Layout	Floor plates	Lobbies & circulation areas
A	Modern with high quality	Flexible	Large	Well-decorated
B	Ordinary with good quality	Flexible	Average-sized	Adequate
C	Plain with basic quality	Less flexible	Small	Basic

Table 2.2 Grading definition for commercial buildings in Hong Kong (others)

Grade	Air Conditioning (AC)	Lift Services	Management	Park facilities
A	Effective central AC	Good zoned	Professional	Normally available
B	Central or free-standing AC	Adequate	Good	Not essential
C	Generally without central AC	Barely adequate/ inadequate	Minimal to average	No

2.2.2 Legislative requirements on energy efficiency

In Hong Kong, the major legislations governing building energy efficiency are as follows:

- B(EE)R (Building Energy Efficiency Regulation): The first energy code was launched in 1995 for the requirement of external walls and roofs of commercial buildings and hotels. The OTTV was further tightened in April 2011 (Environment Bureau *et al*., 2015).
- BEEO (Building Energy Efficiency Ordinance): There are three requirements, including carrying out energy audits in commercial buildings in accordance with

the Energy Audit Code (EAC) every 10 years; ensure the air-conditioning, lighting, electrical and lift/escalator installations comply with the design standards of Building Energy Code (BEC); ensure those installations also comply with BEC when carrying major retrofitting works (Environment Bureau *et al*., 2015).

- EELPO (Energy Efficiency Labelling of Products): It was enacted in 2009 and 2011 covering air-conditioners, refrigerators, compact fluorescent lamps, washing machines and dehumidifiers, and to facilitate the public in choosing energy efficiency appliances for energy saving (Environment Bureau *et al*., 2015).

The work of (Janda, 2008) showed that the legal status of the energy standards for various building sectors (e.g. residential, commercial or both) in 81 countries can be grouped into "mandatory", "voluntary", "proposed" or "no standards". In other places, there are also legislative controls on building energy efficiency. According to a review on 60 developing countries (Iwaro and Mwasha, 2010), the level of progress on energy regulation activities in Africa, Latin America and Middle East was increasing. In Hong Kong, "Wastewi$e Certificate", "Energywi$e Certificate", "IAQwi$e Certificate" and "Carbon Reduction Certificate" were newly launched in 2020 to encourage companies to adopt measures and recognize their efforts in environmental protection. These voluntary schemes help to increase business competitiveness by attracting those customers who value companies that are committed to improve environmental quality as well as to enhance corporate image (Environmental Campaign Committee and Environmental Protection Department, 2021a;b;c;d).

2.2.3 Energy target

As Hong Kong is one of the members of Asian Pacific Economic Cooperation (APEC), it signed the Sydney Declaration and Honolulu Declaration in 2007 and 2011 respectively, for reduction of energy intensity by at least 25% by 2030, and for the whole APEC, reduction of 45% by 2035, using 2005 as base year. To achieve the "Energy Saving Plan for Hong Kong's Built Environment 2015~2025+", it requires partnership of public and private sector. The relative energy saving priorities for commercial and institutional buildings were as follows: (Environment Bureau *et al*., 2015)

1st) Building design and structure;

2nd) Inhabitants' behavior;

3rd) Appliances inhabitants choose to use.

Hence, it is important to assess the energy performance of retrofit facilities in commercial buildings and helps achieve the energy saving plan.

2.2.4 Retro-commissioning and funding from government

Many of the existing buildings were built in the past two decades, where energy saving was not the foremost consideration. To evaluate its building performance, retro-commissioning is a cost-effective approach to identify any operational improvements that can lead to energy saving and lower energy bills. This can be achieved through retrofitting, such as replacing with a more energy efficient appliances (e.g. chillers, pumps, lights, elevators). Even few-year-old buildings can benefit from retro-commissioning because it helps find out any unwanted energy losses such as leakage in building envelope and fault or wrong calibration in equipment (Environment Bureau *et al*., 2015).

To encourage building owners performing energy-cum carbon audits and energy efficiency projects, the HKSAR provided $450 million public funds in 2009 through the Environment and Conservation Fund (ECF). More than 6400, which was about 1/7 of all buildings in Hong Kong participated in this Building Energy Efficiency Funding Schemes (BEEFS) (Environment Bureau *et al*., 2015). As at May 2014, there were 1,115 approved energy efficiency projects under the schemes, with total energy saving about 648 TJ. About two-third of projects were related to lighting or air-conditioning retrofitting with short payback period. At the end of the programme, more applicants applied complex centralized air-conditioning plants and lifts retrofits. The owners became more willing to make bigger investments with longer payback periods once the cost and benefits were clear (Environment Bureau *et al*., 2015). With the funding and subsides from government, more advanced technology (e.g. BIM for facility management, installation of seniors) can be applied in these retrofitting projects, and hence may facilitate the facility managers to obtain more precise data to evaluate their projects.

Shallow renovation projects such as retro commissioning provide savings of 10-20% with an average payback slightly above one year (Nock and Wheelock, 2010). Through retro-commissioning, a total of 2,114,000 kWh/year energy saving potential was identified through the study of the waterside system, airside system, as well as the inter-connected relationship between the systems. The adopted measures included adjusting chiller operation to rectify variable-speed operation and improve efficiency towards the as-designed values, identifying issues with the airside equipment’s chilled water valves affecting the chilled water distribution system efficiency, and adjusting static pressure setpoints and logic of the air distribution system to improve efficiency while maintaining indoor air and thermal quality. Rectification actions included adjustment of setpoints, operation sequence, sensor calibration, budgeting for equipment improvement, and identification of KPIs for continuous monitoring. Examples showed that building performance were improved to achieve about 18% potential reduction of landlord energy consumption through rectification and continuous monitoring (Lok *et. al*, 2020). The survey findings in this paper served as a preliminary stage for drafting an analytic retrofit evaluation method only. For further study, validation from typical commercial buildings cases is important to examine the applicability of performance evaluation.

2.3 Common retrofit strategies

A hierarchical approach for achieving zero carbon building was established, firstly increase energy efficiency through efficient building construction, efficiency systems and appliances (UKDOE, 2018, Xing *et al*., 2011) , then through operations and maintenance and change in user behavior (UKDOE, 2018), and finally addressing remaining needs with on-site renewable energy generation (UKDOE, 2018, Xing *et al*., 2011). Bu *et al*. (2015) summed up the green retrofit design of main technical measures, which consisted of (i) energy-saving building plan and design, and enhancement in maintenance structure of the heat insulation performance; (ii) development of new energy-saving technical measures; (iii) system maintenance and management of energy-saving technical measures; (iv) renewable energy; and (v) indoor environment enhancement. They are discussed as follows:

2.3.1 Energy-saving building plan and design

Improving energy performance of the building may deteriorate the hygrothermal performance of the envelope and to facilitate the reduction of overheating (Bournas *et al*., 2016). The economic performance of retrofitting measures in residential buildings in Turkey was studied with different variables, including window-to-wall ratio, window system, thermal insulation material, and orientation and building age. Highest economic performance ratio was obtained for window-to-wall ratio of 10% at all ages (Cetiner and Metin, 2017).

Besides the amount of materials, the choice of materials also determined the embodied energy and embodied land of the façade (Rios *et al*., 2016). A maximum 67% of carbon emission reduction can be achieved through alternative materials in Hong Kong private residential development scenario cases (Chiang *et al*., 2014). In Mediterranean area, retrofitting green roofs in unwell-insulated building had a remarkable reduction of both cooling and heating load by around 80% and 34% respectively through simulation (Gagliano *et al*., 2014). Green roofs also provided the largest carbon storage potential among the scenarios in evaluation of the sustainable drainage techniques (Warwick and Charlesworth, 2012). Through roofing upgrades, it can benefit small buildings to a greater degree than larger buildings (Chidiac *et al*., 2011b). For larger and more resourceful offices, buildings are recommended to hire an expert team to conduct detailed energy audit and analysis that will contribute to the most cost-effective renovation solutions for the building (Rios *et al*., 2016).

2.3.2 Development of new energy-saving technical measures

There were many innovative technologies such as ventilated façade with photovoltaic panels, electrochromic PV window, seasonal thermal energy storage (STES) etc. (Ahmed, et. al, 2017). By implementing energy improvement measures, peak demand load may be reduced and placing less strain on the power supply infrastructure from a regional and individual building level (Luther and Rajagopalan, 2014). Through load shifting control strategies of building thermal mass, it can reduce more than 30% of daily peak load and achieve cost saving of 8.5% to 29%. For the phase change material in commercial buildings, it can reduce 10% to 57% daily peak load and achieve great cost saving of 10% to 57% (Sun *et al*., 2013). Technological innovations and innovations in construction method such as increase contribution by research programmes is one of the key drivers for building retrofits (Itard *et al*., 2008).

2.3.3 System maintenance and management of energy-saving technical measures

The application of a boiler upgrade was more cost effective for smaller buildings than larger buildings (Chidiac *et al*., 2011b). The most effective energy conservation measures were regulating the indoor set point temperature, use of high frequency electronic ballasts and compact fluorescent lamps with and without using external marquee sign. They contributed an annual energy saving of 56kWh/m^2, 22kWh/m^2 and 29kWh/m^2 respectively in 11 typical banks (Spyropoulos and Balaras, 2011). The most common retrofit objects was lighting system while envelop system was the least common for the pilot-city program in Chongqing, China, (Hou *et al*., 2016). However, reducing the lighting load within a building can have a significant negative impact on the effectiveness of a light dimming strategy when applied concurrently (Chidiac *et al*., 2011a). Combining multiple energy retrofit measures (ERMs) was also found to be not as beneficial as the sum of individual ERM modeling (Chidiac *et al*., 2011a).

In the proposed UK "2030 office", the heat recovery can reduce CO_2 emissions relating to HVAC by 61% (Jenkins *et al*., 2009). The energy performance of ten office buildings located in various climatic zones around Europe was evaluated for 11-month period and guidance were provided to designers to reduce energy use in existing office using latest energy saving and environmental friendly techniques (Santamouris and Hestnes, 2002). Through phase replacement of T8 fluorescent tubes by T5, installation of LED lights in advertising lightboxes, installation of variable-frequency drives on escalators, replacement of insulation of chilled water pipes and stringent control on lights on/off policy etc. resulting a 16% reduction of energy consumption over a two-year period in Hong Kong Convention and Exhibition Centre Management Ltd (Council for Sustainable Development, 2011). There was a potential annual electricity savings of 41% when applied demand control ventilation system in hospital through simulation (Radwan *et al*., 2016).

2.3.4 Renewable energy

The key indicators for zero-carbon building refurbishment were energy demand and renewable energy penetrations (Xing *et al*., 2011). The commercial building in Holyoke, Massachusetts, could meet net-zero energy use after appropriate design manipulations and use of several renewable energy sources (Aksamija, 2015). An 80 MW wind-solar hybrid system was proposed in Zhangbei aiming to reduce wind curtailment. It achieved highest net present value of \$27.67M and 15,470 tons CO_2 reduction per year (Ding *et al*., 2019). The overall energy performance of a ventilated semi-transparent photovoltaic double-skin façade was evaluated and found to have high accuracy and low the root-mean-square error as 2.47% through comprehensive simulation model (Peng *et al*., 2016). The optimum design of solar PV shadings was investigated in Hong Kong and its optimum installation position for solar PV shadings was south facade with 30° tilt angle for maximum electricity generation (Zhang *et al*., 2017). However, there was still a huge gap in initial capital costs between traditional gas boilers (only £600-£2000), ground source heat pump (GSHP) installation (£13-£20,000), air source heat pump (ASHP) (£7-£11,000)and biomass boilers (£5,000 for small systems, and up to £20,000 for bigger ones) (UKGBC, 2018).

2.3.5 Indoor environment enhancement

High heat-generating spaces could be placed on areas receiving less solar irradiation throughout the year (Bournas *et al*., 2016). Using venetian blinds with a 45° inclination angle without shading the upper part of the window was the optimum choice for both visual comfort and electric light use (Bournas *et al*., 2016). The changes of occupant behavior, occupant controls and comfort range can lead to significant energy saving, which were with no or low capital investment (Shao *et al*., 2014). The interaction between occupants and the building and systems (opening and closing windows, adjusting thermostat setpoint, etc.) has an impact on actual energy consumption up to 36% (Becchio *et al*., 2016). The post-occupancy of a large-scale renovation project of head office building in Sydney highlighted the importance of improving indoor environmental quality and reinforced the importance of an integrated and user-responsive approach for building design, development, and management (Thomas, 2010).

2.4 Past building retrofit evaluation studies

2.4.1 Modelling

Early stage decisions in project are very determinant because there can be snowball effect that one decision affects the following decisions (e.g. amount of initiated retrofit projects and impact on society) (Gohardani *et al*., 2015).

TOBUS: Caccavelli and Gugerli (2002) developed the TOBUS methodology and software for evaluating consistent retrofit scenarios and estimated a cost-efficient investment budget in the early steps of a retrofit project.

Distributed Energy Resources Customer Adoption Model (DER-CAM): Stadler *et al*. (2014) made use of an optimization tool, Distributed Energy Resources Customer Adoption Model (DER-CAM), to consider building retrofit measures along with the investment decisions for an Austrian Campus building.

Database of Energy Efficiency Performance (DEEP): Lee *et al*. (2015a) presented the Database of Energy Efficiency Performance (DEEP) which is an SQL database and involves input parameters of prototype building models and the simulation results from energy models.

TRNSYS 17: TRNSYS was developed for modelling renewable energy systems at the beginning. It consists of a structure and component models that allows simulation of renewable and other energy systems. It connects individual components (called "type") together into a complete system model for configuration (Beausoleil-Morrison *et al*., 2014). It requires inputs and parameters to produce output. The changing of input values based on a relative or absolute tolerance. The solution principle of TRNSYS is shown in Figure 2.1. The energy performance of buildings was simulated by the use of TRNSYS in the study of Ascione *et al*., (2017); Ciulla *et al*., (2016); Ferrari and Beccali, (2017), Teres-Zubiaga *et al*., (2015); Valdiserri and Biserni, (2016); Ward and Choudhary, (2014). For example, TRNSYS was used to simulate the power required to meet cooling loads (Ward and Choudhary, 2014), and simulate the passive cooling of the spaces in the summer nights (from 23:00 to 7:00, according to UNI TS 11300-1) (Ferrari and Beccali, 2017). Mathematical correlation was developed to predict thermal energy demand for space heating TEDh in function of the number of heating degree-days. These correlations were achieved from simulated data, and then validated against empirical data (Ascione *et al*., 2017).

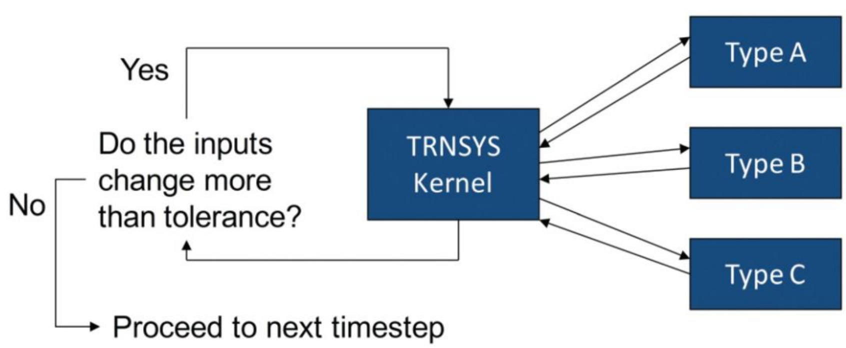

Figure 2.1 TRNSYS solution methodology (Extracted from Beausoleil-Morrison *et al*., 2014)

Giulia *et al*. (2015) developed a 3-D model of the multi-zone building, by use of SketchUp building geometry design tool. It is important to use building performance simulations early in the design process in order to both assess the influence of users' habits on the energy consumption and allows a system check for subsequent further design phases. Zanchini *et al*. (2015) applied TRNSYS 17 to estimate annual use of primary energy and comfort improvement produced from the retrofitting. Annual emission of CO_2 in each retrofit scenario was calculated by employing the European Standard EN 15603:2008 and performed economic analysis (the additional cost with respect to the previous scenario and the total cost have been determined.).

BEES software: In the study of Kneifel (2010), an integrated design approach was used to estimate life-cycle energy savings, carbon emission reduction, and cost-effectiveness of energy efficiency measures among novel commercial buildings by BEES software. 576 energy simulations were operated for twelve prototype buildings with various building types (e.g. office, retail store, school, apartment, etc.) in 16 cities.

DesignBuilder: In the work of Aste and Pero (2013), an iterative empirical-theoretical methodology for energy retrofit of commercial buildings was elaborated by making used of cross-checked measured data, assumptions associated with technical/operational surveys, and building model simulation results as references. This methodology allows a particular and valid determination of critical aspects and intervention priorities to find the best intervention action in terms of technology, economy and energy. Through energy auditing of an educational building by DesignBuilder, Alajmi (2012) produced a list of energy conservation opportunities (ECOs) list, classifying into non-retrofitting (no/minimal cost) which saved 6.5% of the building's annual energy consumption, and retrofitting (with cost) recommendations that can save up to 49.3% by simulation.

EnergyPlus: Chidiac *et al*. (2011a) used the software EnergyPlus for the selection of an optimal set of energy retrofit measures (ERMs) which were affected by climate, occupancy, heating and cooling systems, envelope properties and building geometry. Three cities with different climatic regions, namely Edmonton, Ottawa and Vancouver were also used for the operation of the simulations (Chidiac *et al*., 2011b). Through the use of EnergyPlus computer model simulation, Zhu (2014) found that after renovation the carbon emission in an UK typical office-education building reduced by about 40.8%.

ESP-r: It is a building performance simulation (BPS) tool that strength in modelling building physics. It has well validated methods to model interactions between outdoor and indoor environments and the building fabric (Lee *et al*., 2019). Partitioned solution approach is adopted by ESP-r. Customized solvers are used in each model such as thermal, electric power flow, inter-zone air flow, etc. Therefore, it enables optimal treatment of each equation sets, for example one solver for thermal domain while another for the network air flow. The information was passed between solution domains for interdependencies on time-step, and finally arise the global solution (Beausoleil-Morrison *et al*., 2014) (Figure 2.2).

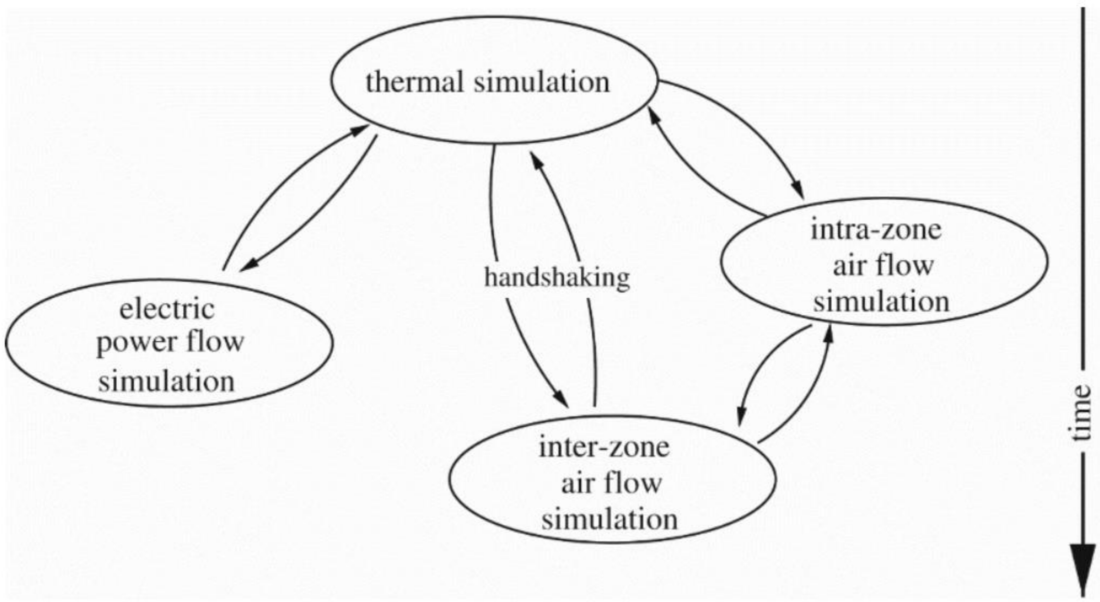

Figure 2.2 ESP-r's partitioned solution approach. (extracted from Beausoleil-Morrison *et al*., 2014)

Asaee *et al*. (2017) validated the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) thoroughly by high-resolution building energy simulation software ESP-r. Gugul *et al*. (2018) was also developed the hourly heating demand model of the dwelling by ESP-r building energy simulation software and validated the model by determining regression coefficient (R^2) and mean absolute percentage error (MAPE) between the estimated and actual daily heating energy consumption.

<u>EnergyPlus:</u> It is one of the widely used BES tool and it is an energy analysis and thermal load simulation program for calculating heating and cooling loads (Shabunko and Mathew, 2018). Rocchi *et al*. (2018) adopted dynamic energy simulation (EnergyPlus 8.5) for an

existing building and comprehensively assessed the performance of different insulation materials added to the building model. The sustainability of several solutions for roof insulation was assessed according to seven criteria derived from the hybrid method developed. They were energy saving, non-renewable energy, comfort performance, global warming, ozone layer depletion, respiratory inorganics, and net present value. Fernandes *et al*. (2018) also applied EnergyPlus for building model; green roof and natural ventilation. Heo *et al*. (2012) adopted model calibration process based on a Bayesian approach and performed calibration by Normative model and Energyplus model. There were also many other studies adopted EnergyPlus to evaluate the building energy performance (Aghamolaei, 2019; Cetiner and Edis, 2014; Cetiner and Metin, 2017; De Tommasi *et al*., 2018; Hong *et al*., 2015; Luddeni *et al*., 2018; Menicou *et al*., 2015; Paiho *et al*., 2015; Pombo *et al*., 2016; Rodrigues and Freire, 2017; Silva *et al*., 2013; Silvero *et al*., 2019; Tadeu *et al*., 2015; Touchie and Pressnail, 2014; Xu *et al*., 2016). Moreover, Mantha *et al*. (2018) also adopted EnergyPlus and eQuest [eQUEST = enhanced DOE-2 + Wizards + Graphics] to analyze the building energy performance and make informed retrofit decisions. The most appropriate set point temperature value was determined by comparing the summary of robot collected ambient temperature data and output ambient temperatures obtained by EnergyPlus simulations. eQUEST also applied in other studies including Xing *et al*., (2015); Touchie and Pressnail (2014).

<u>jEPlus + EA (EEMs Optimization Analysis):</u>

jEPlus is an open-source tool developed for managing complex parametric simulation using EnergyPlus (E+) originally, and it is now coupled with other optimal algorithms

Evolutionary Algorithms (EAs) to provide optimization for building design and operation. The concepts of EAs are that a random set (population) of solutions was repeatedly evaluate the solutions and select better ones for creating new variants until sufficient suitable solutions were found or we have run out of time. Through interfacing EnergyPlus models with optimization algorithms by jEPlus, it can simplify three main tasks including encoding of a building design problem, mapping design solution to a simulation model, and perform simulation duty (Zhang, 2012). Jankovic, (2019) exported the resultant EnergyPlus model subsequently from Design Builder and the type and frequency of its outputs adjusted in EnergyPlus IDF file, to fulfil JEPlus + EA requirements. It reported on the entire process, from establishing the characteristics of the existing building, carrying out design simulations, documenting the off- site manufacture and on-site installation, and carrying out instrumental monitoring, occupant studies and performance evaluation. Luddeni *et al*., (2018) performed EEMs Optimization Analysis: (jEPlus+EA 1.7.6: a GA optimization technique was applied using the jEPlus+EA tool) to significantly reduce the computational time, while still providing accurate results.

<u>Integrated Environmental Solutions Virtual Environment (IES < VE >):</u>

IES is an integrated analysis tool for design and optimization of building retrofits. To obtain energy consumption levels, the Integrated Environmental Solutions Virtual Environment (IES < VE >) software was used in appraising various retrofit building configuration permutations (Oree *et al*., 2016; Tokede *et al*., 2018).

<u>Other simulation softwares:</u>

Fernandes *et al*., (2018) applied Daysim for modelling Daylight and RETSCREEN simulation tool to investigate the annual electric energy produced by the photovoltaic panels. Hong *et al*. (2015) applied Commercial Building Energy Saver (CBES) for a case study of a small office building to demonstrates the use of the toolkit for retrofit analysis. It provided a straightforward and uncomplicated decision-making process for small and medium business owner and leveraging different levels of assessment dependent upon user background, preference, and data availability. Peng *et al*., (2014) adopted Building Model Development and transferred dimension of architectural drawing in AUTOCAD input to DeST and calculated using DeST based on multiple years' meteorological data from Nanjing. Hall *et al*., (2013) adopted energetic hygrothermics building performance simulation (BPS) approach by using Energetic (whole building) hygrothermal simulation software package WUFI Plus v2.1.1.73. Ward and Choudhary (2014) made use of the DELORES simulation (predicted electricity consumption) to perform hourly equipment loads for the thermal analysis. Copiello *et al*., (2017) made used of the Termolog for thermal simulations.

Dodoo *et al*. (2017) applied VIP-Energy, which was a whole building dynamic energy balance program, to perform hour-by-hour calculations of the final energy demand. Leal *et al*., (2015) used the Net Zero Energy Building (NZEB) building energy simulation programme developed in Matlab from another paper. Paiho *et al*., (2015) adopted WinEtana program, which it can automatically suggest typical initial values for occupational and other internal loads, ventilation rates, etc. This analysis tool was developed by a research centre for estimating annual heating and electricity consumptions.

(Wang *et al*., 2015; Wang and Holmberg, 2015) adopted Energy-demand simulation Designed with Excel tools, the model ("Consolis Retro ") - based on the calculation and parametric analysis of building energy demands and applying EN ISO 13790 calculation methodologies. Other software also included Autodesk Green Building Studio software (for evaluating energy saving) (Ruparathna *et al*., 2017), Simapro software (for the assessment of environmental impacts/implementing model and life-cycle inventory), (Cetiner and Edis, 2014; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Tadeu *et al*., 2015), Designbuilder (Aghamolaei, 2019; Pombo *et al*., 2016; Silvero *et al*., 2019), Gabi-lite (for LCA assessment) (Techato *et al*., 2009), IDA Indoor Climate and Energy (ICE) (dynamic simulation tool used for modelling building energy performance). Table 2.3 shows the data analysis methods applied in simulation and Table 2.4 shows a summary of model type and results of previous publications.

Table 2.3 Data analysis methods applied in simulation:

No.	Simulation/Modeling
1	ESP-r (Asaee *et al*., 2017; Gugul *et al*., 2018)
2	JEPlue + EA (EEMs Optimization Analysis) (Jankovic, 2019; Luddeni *et al*., 2018)
3	TRNSYS (Ascione *et al*., 2017; Ciulla *et al*., 2016; Ferrari and Beccali, 2017; Teres-Zubiaga *et al*., 2015; Valdiserri and Biserni, 2016; Ward and Choudhary, 2014)
4	EnergyPlus (Aghamolaei, 2019; Cetiner and Edis, 2014; Cetiner and Metin, 2017; De Tommasi *et al*., 2018; Fernandes *et al*., 2018; Heo *et al*., 2012; Hong *et al*., 2015; Luddeni *et al*., 2018; Mantha *et al*., 2018; Menicou *et al*., 2015; Paiho *et al*., 2015; Pombo *et al*., 2016; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Silva *et al*., 2013; Silvero *et al*., 2019; Tadeu *et al*., 2015; Touchie and Pressnail, 2014; Xu *et al*., 2016)

5	eQuest (Mantha *et al*., 2018; Touchie and Pressnail, 2014; Xing *et al*., 2015)
6	Integrated Environmental Solutions Virtual Environment (IES < VE > (Oree *et al*., 2016; Tokede *et al*., 2018)

No.	**Simulation/Modeling**
7	Designer's Simulation Toolkit (DeST) (Peng *et al*., 2014)
8	Energetic (whole building) hygrothermal simulation software package WUFI Plus (Hall *et al*., 2013)
9	DELORES (Ward and Choudhary, 2014)
10	Termolog (Copiello *et al*., 2017)
11	Daysim (Fernandes *et al*., 2018)
12	Commercial Building Energy Saver (CBES) (Hong *et al*., 2015)
13	SimaPro software (LCA software) (Cetiner and Edis, 2014; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Tadeu *et al*., 2015)
14	Gabi-lite (LCA software) (Techato *et al*., 2009)
15	Designbuilder (Aghamolaei, 2019; Pombo *et al*., 2016; Silvero *et al*., 2019)
16	Autodesk Green Building Studio software (Ruparathna *et al*., 2017)
17	RETSCREEN simulation tool (Ferrari and Beccali, 2017)
18	VIP-Energy (Dodoo *et al*., 2017)
19	IDA Indoor Climate and Energy (Liu *et al*., 2015)
20	Energy-demand simulation Designed with Excel tools (Wang *et al*., 2015; (Wang and Holmberg, 2015)
21	WinEtana program (Paiho *et al*., 2015)
22	Net Zero Energy Building (NZEB) building energy simulation programme (Leal *et al*., 2015)
23	Special program was developed (not mention) (to estimate energy performance of the involved window glazing) (Huang *et al*., 2012)
24	Not specified (Albatici *et al*., 2016; Krarti, 2015; Tadeu *et al*., 2018)

Table 2.4 Model type and results (partly extracted from Ho and Lai, 2018)

No.	References	Model	Building	Result
1	Caccavelli and Gugerli (2002)	TOBUS	Office	A computer-based multimedia program was developed with four subject areas, namely physical state of degradation of building elements, functional obsolescence of building services, energy consumption and indoor environmental quality, which is appropriate for usage by a wide variety of building experts such as office building owners with their own maintenance staff, engineers who are responsible for refurbishment of office buildings, real estate developers and investors, etc.
2	Stadler et al. (2014)	Distributed Energy Resources Customer Adoption Mode (DER-CAM)	Campus Building	This extended version of DER-CAM can consider passive measure improvement options in parallel with the optimal supply technology (such as PV, solar thermal, storage, fuel cells, etc.) decisions during the optimization process, apart from the standard DER investment options such as local renewables or micro combined heat and power (CHP). The results acquired by DER-CAM also demonstrated the complicacy of interactions between DER and passive measure options, implying the need for a holistic optimization method to effectively optimize energy costs and carbon dioxide emissions. For the given energy prices and building improvement costs the best weighted average U value within the optimization results is more or less $0.53 W/(m^2 K)$.
3	Lee et al. (2015)	Database of Energy Efficiency Performance (DEEP)	-	It is an SQL database and involves input parameters of prototype building models and the simulation results from energy models. It includes a recommended set of ECMs that fulfil a user's retrofit investment requirements and provide potential energy cost savings and approximate investment payback years. It enabled transporting the recommended measures from DEEP to more superior the detailed energy modeling using real-time EnergyPlus simulations, thereby speeding up the retrofit actions in SMBs.

Table 2.4 Model type and results (partly extracted from Ho and Lai, 2018) **(Con't)**

No.	References	Model	Building	Result
4	Giulia et al. (2015)	TRNSYS 17 simulation model	-	It proved that the holistic method if used during the diagnostic pre-renovation phase, allows evaluating and planning strategy renovations, as it effectively assesses the multiple effects of the variables and it incorporates the users' perspective. The developed 3-D model of the multi-zone building showed the importance of using building performance simulations (BPS) early in the design process to both assess the influence of users' habits on the energy consumption and become a system check for subsequent further design phases.
5	Zanchini et al. (2015)		Residential	The retrofitting scenario will reduce the total annual use of primary energy (excluding appliances) from 332.5 to 44.8 kWh/m2 and will yield an important improvement of thermal comfort. The proposed retrofit scenario yields a 86.5 % reduction of the use of primary energy, a 86.3 % reduction of CO2 emission, and a relevant comfort improvement. The payback time for private owners is 11 years.
6	Kneifel (2010)	BEES software	Commercial buildings	The results of the study indicated that traditional energy efficiency measures can reduce energy usage in novel commercial buildings by 20-30% on average and up to more than 40% for some building categories and locations. These reductions can often be achieved at negative life-cycle costs since better efficiencies lead to the installation of smaller and more inexpensive HVAC equipment. Apart from energy and cost saving, the modifications even minimize carbon footprint of a building by 16% on average.
7	Aste and Pero (2013)	DesignBuilder	Commercial buildings	This case study was in northern Italy with recent renovation to a high energy performance building, where it was specifically critical since it was surrounded by an urban climatic environment characterized by cold winters and hot summers. The presented case study showed that energy retrofit can produce substantial benefits if carefully planned. A reduction in primary energy consumption by 40 % was achieved through intervention on envelope, without intervention on HVAC plants, lights, or other technical systems.

Table 2.4 Model type and results (partly extracted from Ho and Lai, 2018) **(Con't)**

No.	References	Model	Building	Result
8	Alajmi (2012)	DesignBuilder	Educational building	A list of energy conservation opportunities list was produced and classifying into non-retrofitting (no/minimal cost), which saved 6.5% of the building's annual energy consumption, and retrofitting recommendations that can save up to 49.3% by simulation.
9	Chidiac et al. (2011a)	EnergyPlus	Office	The effectiveness of individual and multiple ERM was assessed and provided a better understanding of their interactive effects. It found that grouping multiple ERMs together was not as advantageous as the addition of individual ERM modelling. Effectiveness of multiple ERMs relies on their interactions. Differences between modelled sets and addition of individual ERMs are much greater for the natural gas consumptions than those for the electrical consumptions among most case studies. To properly obtain the integrated energy consumption pattern, a simulation of all combined ERMs have to be carried out.
10	Chidiac et al. (2011b)		Office	It developed a methodology for screening office buildings for energy efficiency and retrofit potential. The applicability of EnergyPlus was evaluated by comparison of the metered energy consumption of nine office buildings with simulated results. In terms of electrical and natural gas/fuel oil consumptions, the results from the simulations were found to strongly agree with the metered consumption values.
11	Zhu (2014)		Office-Educational building	For the presented case study, the zero-carbon target was hard to achieve by the project passive and active improvement measures. About 40.8% of the carbon emissions reduced due to the application of all retrofit methods. The carbon emission reduced from 6.8 to 1.38 kg/m2 from the heating system with energy saving of 79.4% energy. By improving the air-tightness of the building and the U-value of windows, only 2.2% of carbon emissions can be reduced, while adding renewable devices can contribute to greater carbon saving.

2.4.2 Approach

i) Establishment of new methods/models/framework

In the research work of Juan *et al*. (2010), a hybrid approach which combines A* graph search algorithm with genetic algorithm (GA) was applied. An integrated decision support system was established to evaluate the situations of existing office skyscrapers and propose an optimum set of sustainable retrofit actions taking into consideration of trade-offs between retrofit cost, renovated building quality and environmental effects. In Germany, Shao *et al*. (2014) established a model-based method to support design teams to make multi-criteria decisions for energy-efficiency solutions at the early design stage of office buildings. In UK, Ferreira *et al*. (2014) developed a multi-objective optimization model based on harmony search algorithm for finding an optimal building envelope design that minimized the life cycle costs and carbon emissions. In Italy, Cellura *et al*. (2013) developed an energy and environmental extended input-output model with the life cycle assessment to analyze the role of the building sector for reducing energy consumption and carbon dioxide emissions.

Kamari *et al*. (2017) adopted a multi-dimensional approach involving review of papers, exploration of existing assessment methodologies, carrying out individual and focus group interviews, and application of Soft Systems Methodologies (SSM) with Value Focused Thinking (VFT), and developed a holistic sustainability decision-making framework to support the renovation projects development and communication with stakeholders. Hong *et al*. (2014b) developed a decision support model for establishing the optimal energy retrofit strategy for multi-family housing complexes. Environmental and economic indicators, such as investment cost, replacement cost, Net Present Value (NPV) and saving-to-investment ratio were discussed and the energy saving and carbon dioxide emission reduction effects of nine energy saving techniques were evaluated by using "DesignBuilder" simulation model. Asadi *et al*. (2011) presented a multi-objective optimization model of Tchebycheff programming technique to assist stakeholders to select intervention measures that minimizing energy use in cost-effective way and satisfying the occupant needs.

ii) Review

Almeida and Ferreira (2015) reviewed a methodology, namely International Energy Agency's Energy in Buildings and Communities Annex56 vision which was proposed in decision making process for energy related building renovation. Nielsen *et al*. (2016) provided a state-of-art overview for the development of decision support tools applicable in the pre-design and design of retrofitting projects and classified them into six areas for supporting the decision makers in the renovation process, namely setting sustainability goals, weighting criteria, building diagnosis, generation of design alternatives, estimation of performance, and evaluation of design alternatives. Lee *et al*. (2015b) provided an up-to-date review for 18 energy retrofit analysis toolkits including ECMs (energy conservation measures) and the calculation engine for providing energy and cost saving solutions for commercial buildings. It provided an opportunity to enhance design and development of existing and new retrofit toolkits in the future. Coakley *et al*. (2014) provided a detailed review of current approaches on model development and calibration, in which the calibrated simulation can be categorized into seven areas, namely standards, expense, simplification, inputs, uncertainty, identification and automation. In Australia, Higgins *et* *al*. (2014) evaluated two policy programs including the Green Building Fund and Environmental Upgrade Agreements. It demonstrated how the diffusion model can be a useful resource in tailoring expensive government programs and increasing their effectiveness by forecasting the uptake of each retrofit package.

iii) Elaboration of methods applied

Multicriteria assessment methodology was explained and case studies were conducted in three office buildings in Switzerland. By using ELECTRE III software, the weights and threshold of the retrofitting measures were found by making criterion-by-criterion comparison, global outranking relation, ascending and descending distillation. From the final ranking list generated by the software, solutions that are technically, environmentally, financially and sociocultural valuable can be found (Rey, 2004). In the work of Aste and Pero (2013), an iterative empirical-theoretical methodology for energy retrofit of commercial buildings was elaborated. Cross-checked measured data, operational surveys and building model simulation were used in the study. This methodology allowed effective identification of critical aspects and intervention priorities, thus finding the best intervention action in terms of technology, economy, and energy. Ferreira *et al*. (2014) indicated that the transition between the concept of 'cost optimality' and nearly zero-energy buildings can occur by using the cost optimal method introduced by the EC Delegated Regulation (EU) No. 244/2012, supplementing Directive 2010/31/EU. In the research work of Filippi *et. al* (2020), levelized cost method was used to develop building stock retrofit scenarios and rank the retrofits by levelized cost of saved energy. The demonstration of this method in a house in Italy showed that 60% baseline energy consumption can be saved from doubling the current investments and can be achieved a maximum of 75% saving with over three times of the current investment.

2.4.3 Other methods

Basic calculation and/or validation

Basic calculations were performed to evaluate building retrofit such as payback analysis, energy saving rate, Cost of conserved energy, Net present value, Internal rate of return) (Cetiner and Edis, 2014; Xu *et al*., 2016), thermal performance of the wall compared to measurement (Johansson *et al*., 2016), CO_2 Emissions (Afshari *et al*., 2014), the annual GWP and initial investment cost (Shao *et al*., 2014), energy consumption (de Santoli *et al*., 2014) and energy saving from system (Dall'O *et al*., 2012; Huang *et al*., 2012). The conservation score for each energy efficiency measure was calculated by Roberti *et al*., (2017). The Power Bonus Method was employed to estimate the primary energy factor before and after retrofitting by Wang *et al*., (2015). The IPCC assessment method was used by (Tadeu *et al*., 2015). The dwelling energy assessment procedure (DEAP), which was similar to the UK Standard Assessment Procedure (SAP), was used to calculate the operational consumption in the new building (McGrath *et al*., 2013).

Other calculations included spreadsheet calculation model (Leal *et al*., 2015), by referring to standards or comparing the calculation with actual results (Bleyl *et al*., 2019; Cetiner and Metin, 2017; Copiello *et al*., 2017; Liu *et al*., 2015; Liu *et al*., 2018; Rocchi *et al*., 2018; Wang and Holmberg, 2015; Zheng and Lai, 2018; Zuhaib *et al*., 2018). By referring to reference level in standards, the performance of thermal comfort (PMV & PDD), acoustic comfort (A-weighted sound pressure level, LA_{eq}), daylight conditions (illuminance level); IAQ conditions (pollutants level) and air tightness were known (Silva *et al*., 2013). The simulation error between calibration and actual value were found (Song *et al*., 2017; Xu *et al*., 2016). Validation was also performed to compare the predicted energy consumption or weather conditions with the actual data (Cetiner and Edis, 2014; Gugul *et al*., 2018; Liu *et al*., 2015; Oree *et al*., 2016; Pombo *et al*., 2016; Song *et al*., 2017; Teres-Zubiaga *et al*., 2015; Ward and Choudhary, 2014; Xing *et al*., 2015).

Algorithm

Differential evolution (DE) algorithm was applied (Dodoo *et al*., 2017; (Gugul *et al*., 2018; Silvero *et al*., 2019; Wang *et al*., 2014), for example, to find out the estimated and actual daily heating energy consumption. Original C implementation of the algorithm was another method which can handle real and categorical (coded as binary strings) variables (Roberti *et al*., 2017). Multi-objective optimization with the algorithm NSGA-II was adopted (Roberti *et al*., 2017) which is a genetic algorithm based on non-dominated sorting.

Analytical Hierarchy Process (AHP) and other approaches

Simulation optimization approach was adopted by Shao *et al*., (2014) and applied an analysis model based on the multiple-attribute value theory (MAVT), which is a particular kind of multiple-criteria decision-making (MCDM) techniques to access the qualities of the optimal solutions, and an analytical hierarchy process model was embedded in this tool as well. AHP was also applied in a three-grade evaluation system for heat metering and energy efficiency retrofit of existing residential buildings in northern heating areas of China (Zhao *et al*., 2009a). AHP was used to quantify the conservation compatibility of energy retrofits (Roberti *et al*., 2017) and can apply with Monte Carlo simulation to evaluate the building retrofit performance (Kumbaroglu and Madlener, 2012; Menicou *et* *al*., 2015). Other retrofit evaluation methods included statistic approach (judgment sampling) (Albatici *et al*., 2016), prevailing approach (this approach is based on the integration of monitoring studies and simulation methods.) (Song *et al*., 2017) and k-means clustering (Deb and Lee, 2018).

Sensitivity analysis and risk analysis

Sensitivity analysis was performed in various studies (Bleyl *et al*., 2019; Ciulla *et al*., 2016; De Tommasi *et al*., 2018; Ferrari and Beccali, 2017; Gugul *et al*., 2018; Liu *et al*., 2018; Luddeni *et al*., 2018; Pombo *et al*., 2016; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Song *et al*., 2017; Tadeu *et al*., 2018; Wang and Holmberg, 2015). It can be used to find out the slope of the linear regression signifies the sensitivity factor or priorities of actions based on improving energy efficiency and economic feasibility. Risk analyses were also used in some studies (Hong *et al*., 2015; McArthur and Jofeh, 2016; Silvero *et al*., 2019).

Other analysis methods

Quantitative bundle analysis (financial aspect) was performed (McArthur and Jofeh, 2016) to develop the weighting score factor by five-point scale. The cost, energy and water use, CO_2 emission, potential for energy rating and NPV were considered during the evaluation process. Several Marginal Abatement Cost Curves (MACCs) was developed as a decision support tool for the design urban-level demand-side management programs (Afshari *et al*., 2014). For qualitative analysis, the evaluation elements included user control, thermal, acoustic, compliance with codes and standards, performance prediction accuracy; overall score (McArthur and Jofeh, 2016). Bundle performance summary were then found with its overall score of financial, qualitative, risk performance. (McArthur and Jofeh, 2016). Through a quantitative analysis of a building adaptation database, the nature and extent of adaptations to premium offices were identified and quantified in respect of attributes, for example, adaptation level, building age, location, construction form, envelope, shape and height and operating costs.

Network model

Mathematical model was established based on multi-index comprehensive evaluation method combined with life cycle assessment theory, post-evaluation thought and successful degree evaluation method (Zhao *et al*., 2009a). Parameter screening technique, known as the Morris method (rank parameters by their relative effect on the energy consumption of the building was adopted by executing with Simlab version 2.2 (Heo *et al*., 2012). Multi-objective optimization and artificial neutral networks, called CASA (couples Energy Plus and MATLAB) were adopted (Ascione *et al*., 2017). It combined with three methodologies: 1. CAMO (Cost-optimal analysis by multi-objective optimization (MOGA): to select recommended packages of energy retrofit measures, allows to explore a wide domain of retrofit scenarios); 2. SLABE (simulation-based large-scale uncertainty/sensitivity analysis of building energy performance) and 3. ANNs (artificial neural networks).

The quality function deployment tool (QFD) was developed by Shao *et al*., (2014). It was a "method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process" and it was driven by the main tool called House of Quality (HoQ). Another models for evaluating building retrofits included neural network model (Asaee *et al*., 2017) and multi-objective input-output model by multi-objective linear programming model (MOLP) (bottom-up approach) (Henriques *et al*., 2015).

Life cycle cost

A combination of input–output analysis (IOA) and the life cycle assessment (LCA) were adopted to evaluate energy consumption (indirect energy rate) and CO_2 emissions due to the realization of the retrofit actions; direct energy saving and avoided CO_2 emissions after the realization of the retrofit actions; and indirect energy saving and avoided CO_2 emissions, due to the missed production of the direct rate of energy (Cellura *et al*., 2013). Mixed-integer linear program (MILP) was used to identify in a systematic manner the best alternatives for reducing the environmental impact of buildings, which optimized maximum energy savings as unique environmental criterion. It extended to include other environmental impacts that are quantified following LCA principles (Antipova *et al*., 2014). Many other studies also applied life cycle cost in their evaluation (Bleyl *et al*., 2019; Cetiner and Metin, 2017; Copiello *et al*., 2017; Luddeni *et al*., 2018; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Wang *et al*., 2014).

Life cycle assessment

Seven impact categories including abiotic depletion potential, non-fossil abiotic depletion potential, fossil acidification potential (kg SO_2eq), eutrophication potential, global warming potential (kg CO_2eq), ozone layer depletion potential, photochemical ozone creation potential) were used in Pombo *et al*. (2016). Interrelated steps (e.g. 1. definition of goal and scope, 2. life-cycle inventory (LCI), 3. life-cycle impact assessment (LCIA) and 4. interpretation (ISO14040:2006) were adopted in Cetiner and Edis (2014); Tadeu *et al*., (2015). Other studies that applying LCA includes Afshari *et al*. (2014); Antipova *et al*. (2014); Cetiner and Edis (2014); Huang *et al*. (2012); McGrath *et al.* (2013); Techato *et al.* (2009); Rocchi *et al*. (2018); Ruparathna *et al*. (2017); Wang *et al*. (2015). For Wang and Holmberg (2015), retrofit option rankings with life-cycle cost analysis (LCCA) was used. Life Cycle Cost and Benefit Analysis (LCCBA) was adopted by Bleyl *et al*. (2019). LCIA methods were used by Cetiner and Edis (2014); Rodrigues and Freire (2017); Shao *et al*. (2014). In the study of Rodrigues and Freire (2017), cumulative energy demand was used to measure the non-renewable primary energy to address energy resource depletion. Table 2.5 shows the data analysis methods applied other than simulation.

Table 2.5 Data analysis methods applied other than simulation

Analysis Method	References
Basic calculation and/or validation	(Afshari *et al*., 2014; Bleyl *et al*., 2019; Cetiner and Edis, 2014;Cetiner and Metin, 2017; Copiello *et al*., 2017; Dall'O *et al*., 2012; de Santoli *et al*., 2014; Gugul *et al*., 2018; Huang *et al*., 2012; Johansson *et al*., 2016; Leal *et al*., 2015; Liu *et al*., 2015; Liu *et al*., 2018; McGrath *et al*., 2013; Oree *et al*., 2016; Pombo *et al*., 2016; Roberti *et al*., 2017; Rocchi *et al*., 2018; Shao *et al*., 2014; Silva *et al*., 2013; Song *et al*., 2017; Tadeu *et al*., 2015; Teres-Zubiaga *et al*., 2015; Wang and Holmberg, 2015; Wang *et al*., 2015; Ward and Choudhary, 2014; Xing *et al*., 2015; Xu *et al*., 2016; Xu *et al*., 2016; Zheng and Lai, 2018; Zuhaib *et al*., 2018)
Algorithm	(Dodoo *et al*., 2017; Gugul *et al*., 2018; Roberti *et al*., 2017; Silvero *et al*., 2019; Wang *et al*., 2014)
Analytical Hierarchy Process (AHP) and other statistic/prevailing approaches	(Albatici *et al*., 2016; Deb and Lee, 2018; Kumbaroglu and Madlener, 2012; Menicou *et al*., 2015; Roberti *et al*., 2017; Shao *et al*., 2014; Song *et al*., 2017; Zhao *et al*., 2009a)
Sensitivity analysis & Risk analysis	(Bleyl *et al*., 2019; Ciulla *et al*., 2016; De Tommasi *et al*., 2018; Ferrari and Beccali, 2017; Gugul *et al*., 2018; Hong *et al*., 2015; Liu *et al*., 2018; Luddeni *et al*., 2018; McArthur and Jofeh, 2016; Pombo *et al*., 2016; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Silvero *et al*., 2019; Song *et al*., 2017; Tadeu *et al*., 2018; Wang and Holmberg, 2015)

Other analysis methods (e.g. Quantitative bundle analysis)	(Afshari *et al*., 2014; McArthur and Jofeh, 2016; Wilkinson, 2012)

(Cont')

Analysis Method	References
Network Model	(Ascione *et al*., 2017; Henriques *et al*., 2015; Heo *et al*., 2012; Shao *et al*., 2014; Zhao *et al*., 2009a)
Life Cycle Cost	(Antipova *et al*., 2014; Bleyl *et al*., 2019; Cellura *et al*., 2013; Cetiner and Metin, 2017; Copiello *et al*., 2017; Luddeni *et al*., 2018; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Wang *et al*., 2014)
Life Cycle Assessment	(Afshari *et al*., 2014; Antipova *et al*., 2014; Bleyl *et al*., 2019; Cetiner and Edis, 2014; Huang *et al*., 2012; McGrath *et al*., 2013; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Shao *et al*., 2014; Tadeu *et al*., 2015; Techato *et al*. 2009; Wang and Holmberg, 2015; Wang *et al*., 2015)

As reviewed above, many studies have demonstrated the application and importance of evaluation of building retrofits, and they can be evaluated through simulation and verification of its actual performance (Figure 2.3).

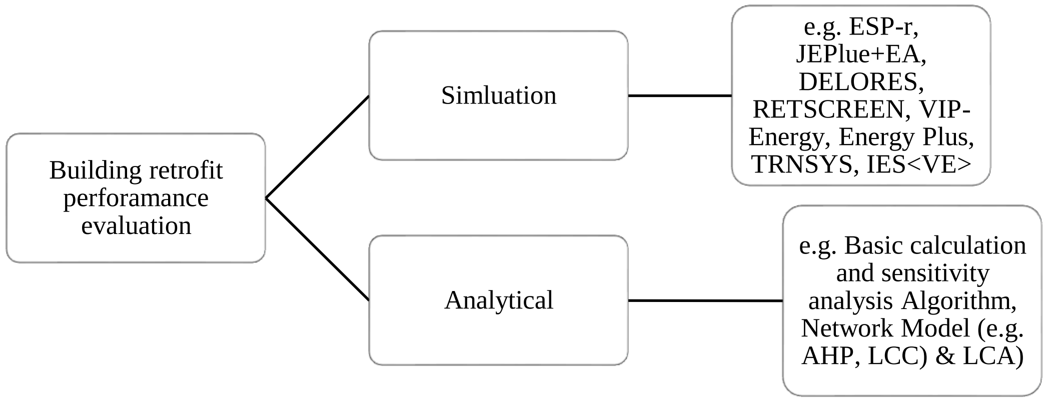

Figure 2.3 Simulation and analytical approach for building retrofit performance evaluation

Among the above simulation and analytical methods, this study adopted ANP method for prioritizing KPIs in building retrofits performance evaluation. According to Aragonés-Beltrán *et al*. (2014), AHP/ANP-based decision analysis approach has the following advantage, and reasons for applying in this study are: "(i) allowing decision makers to analyze complex decision-making problems using a systematic approach that breaks down the main problem into simpler and affordable subproblems, (ii) if there are interdependencies among groups of elements, ANP should be used, (iii) the detailed analysis of priorities and interdependencies between clusters' elements forces the decision makers to carefully reflect on his project priority and on the decision-making issue, which results in a better knowledge of the issue and a more reliable final decision.". Moreover, ANP has already been widely applied for performance evaluation (Kheybari *et. al*, 2020) in construction industry, such as evaluate the performance of adaptive façade systems in complex commercial buildings (Yitmen, *et al*., 2021), select the most sustainable material for building enclosure (Mahmoudkelaye *et al*., 2018) and evaluate the energy retrofit solutions in historical (Roberti et al., 2017) and residential buildings (Silvero *et al*., 2019). Chapter 3 will discuss more on the research methodology.

2.4.4 Real application examples

A five-year longitude study was performed in a Hong Kong typical commercial building and a novel indicator, carbon reduction efficiency was introduced for evaluating integrated retrofits performance of environmental and economical aspect (Zheng and Lai, 2018). From year of 2006 to 2010, Langham Place Hotel Mongkok Hong Kong adopted retrofit measures such as replacement of different lightings, air-conditioning retrofitting measures such as chiller water temperature setback, extra chiller pump for top-level function room, waste management and logistics planning, and achieved about ten-fold increase in energy saving, rising from around 84,000kWh/pa to 826,000 kWh/pa (Cheung and Fan, 2013). The renovation project at the Chow Yei Ching Building of the University of Hong Kong, included chilled water plant upgrading and optimization, building management system upgrading and with energy monitor and controlling, lighting retrofits, window film, solar panel, aimed at achieving 30% energy savings, and a 1-year testing will be conducted to verity the simulated energy savings (Sun and Lau, 2015).

In UK, a socio-technical building performance evaluation approach was adopted and found there were significant difference between the modelled and actual carbon emissions of the retrofits (Gupta and Gregg, 2016). In Denmark, the comprehensive retrofit of apartment complex included new facades and windows, additional insulation, mechanical ventilation with heat recovery and a photovoltaic installation on the roof. The energy hence reduced significantly by 31%, from 139.1 kWh/m^2/year to 95.6 kWh/m^2/year (Thomsen *et al*., 2016). In Australia, it highlighted the four schools of 1960s-1970s can achieve reduction of more than 80% in heat demand (Dequaire, 2013). In UK, social housing providers were aware of the sustainable retrofit agenda, but with varying levels of strategic readiness

(Swan *et al*., 2013). If the building stock was renovated at nearly 2.5% of its floor space per year, more than half of the energy used by the stock could be reduced (Atkins and Emmanuel, 2014). Table 2.6-2.7 shows the key summary finding. Table 2.8 shows a summary of 30 relevant and recent publications. But there has been limited research that aims to develop an analytical method for evaluating the holistic performance of building retrofits (Mantha *et al*., 2018; Gonzalez-Caceres *et al*., 2019; Liu *et al*., 2018; Rocchi *et al*., 2018; Ruparathna *et al*., 2017). To help building owners and facilities managers make decisions on building retrofits, it is essential to identify indicators for developing an analytic method for evaluating the holistic performance of building retrofits.

Table 2.6 Different aspects in retrofit (partly extracted from Ho and Lai, 2018)

No.	References	Country/City	Building Type	Result	Aspects
1	Zheng and Lai (2018)	Hong Kong	Commercial building	Total electricity consumption reduction of 32.3%, equivalent to 42.9% carbon emission reduction after implementation of energy saving measures.	Technical and Economical
2	Cheung and Fan (2013)	Hong Kong	Hotel	Ten-fold increase in energy saving.	Technical
3	Sun and Lau (2015)	Hong Kong	University	Aimed to achieved 30% energy saving.	
4	Thomsen *et al.* (2016)	Denmark	Apartment complex	Energy consumption reduced significantly by 31%.	
5	Dequaire (2013)	Australia	School	All four cases of large buildings built in 1960s – 1970s can achieve reduction of more than 80% in heat demand.	
6	Gupta and Gregg (2016)	UK	Residential	Significant difference between the modelled and actual carbon emissions of the retrofits.	Socio-technical
7	Swan *et al.* (2013)	UK	Social housing sector	Social housing providers were aware of the sustainable retrofit agenda, but with varying levels of strategic readiness.	Social
8	Atkins and Emmanuel (2014)	UK	Office for voluntary sector	The energy uses the case studied type buildings could be halved with comparable savings in CO_2emission.	Technical (PoE)

Table 2.7 Data period, collection method, study approach and results (partly extracted from Ho and Lai, 2018)

No.	Data period	Data collection method	Approach	Major results
1	Five years (2011-2015)	1. Monthly energy end-uses 2. Cost data of energy saving measures	Calculated 1. Carbon emission; 2. Net Present Value and Return of investment	A novel indicator, carbon reduction efficiency, was introduced for evaluating integrated environmental and economic performance of retrofits. The degradation effect of retrofits was also considered for more accurate energy consumption assessment.
2	Monthly data spanning 36 months	Five measurements: 1. Units of energy consumed (kWh) 2. No. of cooling degree days 3. No. of heating degree days 4. No. of occupied rooms 5. No. of food covers	Studied the correlation coefficients between the five measurements	CO_2 emissions were reduced by a total of approximately 1900 tonnes through replacement of lighting installation, adoption of water-cooled chillers and heat pump water heaters, variable speed drives and water saving devices. It estimated that there was about 10-fold increase in the amount of energy saved in five years (2006-2010).
3	-	1. Occupancy patterns 2. Base-year electricity consumption 3. Investment budget and return cycle 4. Environmental conditions 5. Details of mechanical and electrical systems	Adopted five facility improvement measures such as chiller water plant upgrading and optimization, building management system upgrading with energy monitor and controlling, etc.	Provided a real project of energy auditing for existing buildings and study how to optimize the operation and maintenance (O&M) of building (promised to have 30% energy savings, while will trace the record 1 year later).
4	Heating season 2011-2012 (before renovation) and 2012-2013 (after renovation)	1. Questionnaire; 2. Measurement of ventilation conditions by passive tracer gas technique; 3. Energy consumption for heating and domestic hot water (DHW) before and after the energy retrofitting	Calculations through ASCOT (assessment tool for additional construction cost) - method based on methodology of EN ISO 13790.	Good agreement between calculated and measured heating consumptions. The measured energy consumption for heating and domestic hot water before and after renovation was 139.1 kWh/m^2/year and 95.6 kWh/m^2/year respectively. For the 12.9% (8.6% net) increase in rent, tenants received a better indoor climate.

Table 2.7 Data period, collection method, study approach and results (Cont') (partly extracted from Ho and Lai, 2018)

No.	Data period	Data collection method	Approach	Major results
5	-	1. Site visits (e.g. outside inspections, indoor exploration and technical room visit); 2. Interviews with key personnel (e.g. architects and engineers involved in the projects); 3. Users answered questions during the visits; 4. Heat demand before and after the planned refurbishment	Data collection protocol were designed based on a general understanding of passive house concepts for interviews and data collection to guarantee the reliability of the research.	Four cases of this research highlight that retrofits of large buildings achieve reductions of more than 80 % in heat demand, compared to the original traditionally planned refurbishment.
6	Over two years	1. Site visit; 2. Survey; 3. Questionnaire & interview; 4. In situ-measurement and monitoring	Adopted socio-technical building performance evaluation (BPE) approach	Post-retrofit, the Victorian house achieved nearly 75% CO_2 reduction, while only 57% CO_2reduction for the modern house over the baseline emissions due to i) higher than expected air permeability rates, ii) installation issues with micro-renewable systems, iii) lack of proper commissioning, iv) usability of controls, v) occupant preferences and behaviour.
7	-	Questionnaire (Web-based structured survey, 20 questions in total)	Studied the following social issue: 1. Perception of retrofit as a challenge 2.Strategic intent regarding retrofit 3.Perceived drivers and barriers for the adoption of retrofit	Social housing providers were aware of the sustainable retrofit agenda, but with varying levels of strategic readiness. Immediate benefits to residents was important driver, as opposed to more remote issues such as climate change. The emerging nature of the sustainable retrofit market was a major potential risk for residents.
8	a. Five years b. 3 months	a. Weekly metre readings; b1. Building User Satisfaction survey; b2. Thermal imaging; b3. Indoor temperature; b4. Structured interviews with key personals	Applied Three PoE protocols: 1..BREEAM; 2.The Soft Landings approach 3. Design quality method	Refurbishment of building continued to deliver the design intentions, even 15 years after the refurbishment, and meeting the Scottish Government's emission reduction targets for 2020 and 2050.

Table 2.8 Summary of relevant publications on retrofit performance evaluation (extracted from Ho *et al*., 2021)

No.	Authors (year)	Study method	Aspect	Building type	Main result
1	Hong et al. (2015)	Energy retrofit analysis toolkit (Commercial Building Energy Saver - CBES)	Environmental Economic	Office	The applicability of CBES for web-based retrofit analyses based on load shapes, benchmarking and pre-simulated databases of retrofit measures is demonstrated.
2	Wang et al. (2015)	Consolis Retro simulation and life cycle assessment techniques	Environmental	Residential	High operational energy-saving measures may not always lead to larger reduction in both embodied energy and greenhouse gas emissions, particularly for building envelope retrofitting.
3	Xing et al. (2015)	Software (eQuest) and survey	Environmental	Hotel	A hierarchical process with embedded techniques (insulations, energy efficient equipment and micro-generation) is presented as a pathway towards zero-carbon building refurbishment.
4	Albatici et al. (2016)	Site visit and survey	Environmental Economic	Social Housing	An operating methodology for the optimization of the retrofitting process based on energy efficiency and cost-effectiveness is presented.
5	Johansson et al. 2016)	Site measurements	Technical	Apartment	Measurements of the temperature and relative humidity in the wall studied show no sign of deterioration of the vacuum insulation panels and there is a low risk for condensation in the construction.
6	McArthur and Jofeh (2016)	Qualitive bundle and qualitative analysis (such as thermal comfort, acoustic quality)	Environmental Economic Users' perspective	Office; portfolio optimization for a large tenant (education institution)	A mathematical model is presented, which addresses the challenge of identifying the most strategic investments to make within a building portfolio for retrofit evaluation.

No.	Authors (year)	Study method	Aspect	Building Type	Main result
7	Oree et al. (2016)	Interviews, measurement, and energy audit	Economic	Office	Lighting retrofit achieved the most significant reduction while measures that improved the thermal envelope of the building resulted in energy savings.
8	Pombo et al. (2016)	Simulation (EnergyPlus) and life cycle assessment	Environmental Economic	Residential	The required additional investment for obtaining an overall performance improvement of the building envelope is relatively low when considering the life cycle environmental and financial savings.
9	Valdiserri and Biserni (2016)	Simulation (TRNSYS)	Economic	Office	The window replacement option was found to be unprofitable even though it appears to be the first and simplest action to be performed.
10	Ascione et al. (2017)	Simulation (TRNSYS)	Users' Perspective Environmental	Office	The achieved cost-optimal solution produces a large amount of global cost savings and significant reductions of energy consumption, discomfort hours and polluting emissions.
11	Dodoo et al. (2017)	Simulation (whole building dynamic energy balance program: VIP-Energy)	Environmental	Residential	The study shows that assumed indoor air temperature, internal heat gains and efficiency of ventilation heat recovery units have significant effect on the energy performance of the studied building and energy efficiency measures.
12	Ferrari and Beccali (2017)	Simulation (TRNSYS and RETSCREEN)	Economic	Office	Through exploiting on-site renewable energy sources, the net energy consumption can be near zero.
13	Roberti et al. (2017)	Simulation (EnergyPlus)	Users' Perspective Environmental	Historical	The case analyzed shows a four-fold reduction in energy needs at a high thermal comfort level.
14	Ruparathna et al. (2017)	Simulation and life cycle cost (LCC) analysis	Economic Environmental	Office	The fuzzy-based approach enables the forecasting of future LCC from the changes in macro-economic factors.
15	Song et al. (2017)	Simulation (TRNSYS)	Economic Environmental	Office	Significant energy savings are obtained for the thermal transmittance of exterior walls infiltration rate, ventilation and shading coefficient.

No.	Authors (year)	Study method	Aspect	Building Type	Main result
16	Gugul et al. (2018)	Simulation (ESP-r)	Economic Environmental	Residential	Applying window glazing, roof, and a combination of window, wall, and roof improvements can significantly reduce the heating energy demand.
17	Mantha et al (2018)	Simulation (EnergyPlus and eQuest)	Economic Environmental	University	The proposed methodology of mobile indoor robotic monitoring and data collection of ambient parameters is effective and economical when compared with the traditional methods.
18	Tokede et al. (2018)	Simulation (Integrated Environmental Solutions Virtual Environment software)	Economic	Office	The impact of revocability in life cycle appraisal of a retrofit building project reveals that it can be about one-quarter in retrofit buildings.
19	Deb and Lee (2018)	Analysis of energy audit data by k-means clustering	Environmental	Office	The best set of variables consists of: 1) gross floor area (GFA), 2) non-air-conditioning energy consumption, 3) average chiller plant efficiency, and 4) installed capacity of chillers.
20	De Tommasi et al. (2018)	Simulation (EnergyPlus)	Environmental	Office	The synergy of detailed equipment models and optimized control algorithms with existing state-of-the-art simulation tools enables a very accurate evaluation of key performance indicators.
21	Fernandes et al. (2018)	Used simulation models (e.g. EnergyPlus)	Economic Environmental Users' Perspective	University	A procedure is demonstrated, which helps designers and decision makers to choose the best retrofit strategy considering energy consumption, thermal comfort and cost-benefit.
22	Luddeni et al. (2018)	Simulation (jEPlus+EA)	Economic Environmental	Office	The building stock was shown to have a significant amount of primary energy savings when retrofitted through optimal combinations of energy efficiency measures and rooftop integrated photovoltaics.
23	Rocchi et al. (2018)	Used simulation models (e.g. EnergyPlus) and life cycle assessment	Economic Environmental Users' Perspective	Farmhouse	The result shows the division of the studied insulation materials into three categories of energy performance: bad, medium and good.

No.	Authors (year)	Study method	Aspect	Building Type	Main result
24	Zheng and Lai (2018)	Analysis of empirical energy and cost data	Economic Environmental	Commercial	An indicator called 'carbon reduction efficiency' was developed to assess the performance of retrofits and a pragmatic approach to evaluating retrofit projects in real-world buildings was illustrated.
25	Zuhaib et al. (2018)	Survey, measurements, and calculation	Users' Perspective	University	Ad-hoc retrofitting of the façade studied does not make any significant difference to indoor environmental quality, and occupants continue to adapt personally to the existing conditions.
26	Aghamolaei (2019)	Simulation (EnergyPlus)	Environmental	Residential	Significant reduction in energy can be achieved by application of the proposed retrofit scenarios.
27	Bleyl et al. (2019)	Used a dynamic Life Cycle Cost and Benefit Analysis to model the cash flows	Economic Environmental Health and Safety Users' Perspective	Office	Results of the dynamic model provide solid grounds for deep energy retrofit business case analysis, project structuring, financial engineering, and policy design.
28	Jankovic (2019)	Simulation (JEPlue + EA)	Technical Economic Users' perspective	Residential	Building physics parameters before and after retrofit are evaluated through simulation of dynamic heating tests with calibrated models, and the method can be used as quality control measures in future retrofit programmes.
29	Dall'O' et al. (2020)	Simulation analyses conducted in accordance with the LEED protocol	Environmental	School	Decision-making tools and indicators supporting energy and environmental retrofit actions for schools are provided.
30	Okorafor et al. (2020)	Used a mixed method research (pilot study, focus group discussion and surveys) and analyzed data using statistical methods and content analysis	Environmental	-	A set of guidelines comprising of seven stages for managing successful building energy retrofit projects are elucidated.

2.5 Retrofit indicators identification process

To acquire a clear understanding of the research area, a mixed methods approach combining positivism and interpretivism was taken. First, a four-stage review process were adopted in the study for reviewing paper published from 2000 to April 2019. This part of work was similar to the reviews presented by Lee *et al*. (2015b) and Lai and Man (2018a). The key information including indicators or features of building retrofit performance evaluation were identified. After identifying the key performance indicators for building retrofit from literature, a focus group study (c.f. Wilkinson (1998) and Lai and Man (2018b) was conducted to examine their importance rating through adopting a five-point scale. The important KPIs were shortlisted for further investigation of their inter-relationship and applicability. They were also categorized into the four major aspects (viz. economic, environmental, health and safety, and users' perspective).

The literature review process followed the four-stage systematic approach of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Figure 2.4): (i) identification; (ii) screening; (iii) eligibility; and (iv) including. In the first step of Stage 1, publications were searched from five renowned literature databases, namely, Business Source Complete, Emerald Management eJournals, ProQuest ABI/INFORM Collection, Scopus, and Web of Science and the keywords used were "building", "retrofit" and "evaluation". Since there are synonyms of some words (e.g. the meanings of "assessment") and of the word "evaluation" are similar), such synonyms were included in the keyword search. To cater for different word forms (e.g. "evalut*" embraces "evaluate", "evaluates" and "evaluated"), further keywords used included "analysis" (analy*), "assess" (assess*), and "appraisal" (apprais*).

Consequently, a total of 480 publications were found from this step. To refine the search results, a further step was taken to sort the publications by subject areas “construction building technology”, “green sustainable science technology”, “engineering environmental”, “economics”, “management”, “business finance”, etc. Then, publications in engineering related journals, amounting to 221, were identified.

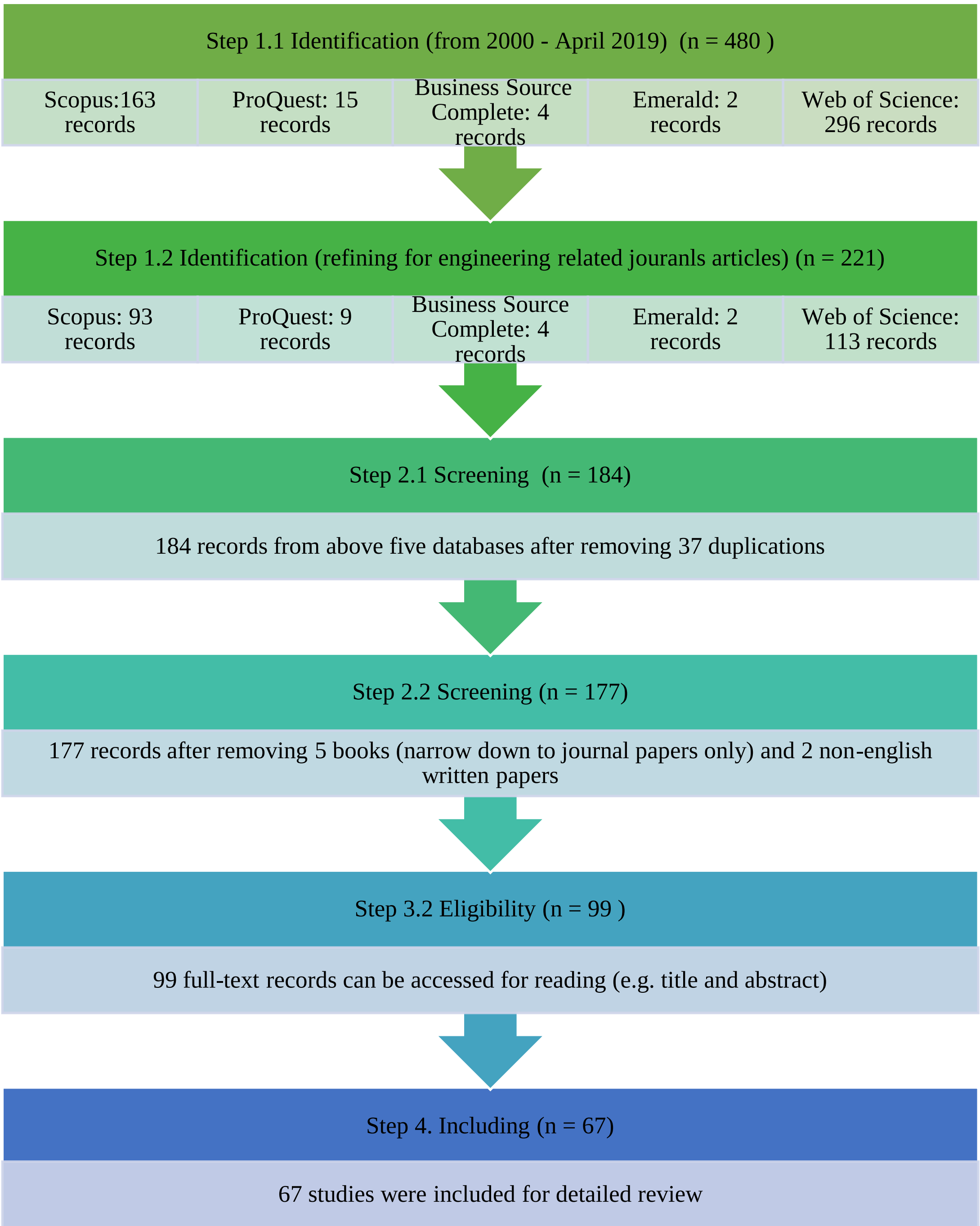

Figure 2.4 PRISMA flowchart for literature review (extracted from Ho et al., 2021)

The search result of from databases were shown in Table 2.9a to Table 2.9f.

Table 2.9a. Search result in Emerald

No.	Content Item Title	After refining for engineering journals	Related to our topic
1	evaluation AND retrofit AND building	0	0
2	analysis AND building AND retrofit	1	1
3	appraisal AND building AND retrofit	0	0
4	assess AND building AND retrofit	1	1
	Duplicated		0
	Total	**2**	**2**

Table 2.9b. Search result in Web of Science

No.	TI (Title)	After refining for engineering journals	Related to our topic
1	evaluat* AND retrofit AND building	26	17
2	analy* AND building AND retrofit	48	43
3	apprais* AND building AND retrofit	1	1
4	assess* AND building AND retrofit	38	20
	Duplicated		(-3)
	Total	**113**	**79**

Table 2.9c. Search result in Scopus

No.	TI (Title)	After refining for engineering journals	Related to our topic
1	evaluat* AND retrofit AND building	27	12
2	analy* AND building AND retrofit	41	23
3	apprais* AND building AND retrofit	2	1
4	assess* AND building AND retrofit	23	9
	Duplicated		(-27)
	Total	**93**	**18**

Table 2.9d. Search result in ProQuest (AB/INFORM)

No.	TI (Title)	After refining for engineering journals	Related to our topic
1	evaluat* AND retrofit AND building	2	1
2	analy* AND building AND retrofit	6	4
3	apprais* AND building AND retrofit	0	0
4	assess* AND building AND retrofit	1	1
	Duplicated		(-6)
	Total	**9**	**0**

Table 2.9e. Search result in Business Source Complete

No.	TI (Title)	After refining for engineering journals	Related to our topic
1	evaluat* AND retrofit AND building	0	0
2	analy* AND building AND retrofit	4	1
3	apprais* AND building AND retrofit	0	0
4	assess* AND building AND retrofit	0	0
	Duplicated		(-1)
	Total	**4**	**0**

Table 2.9f. Inclusion table during the reviewing process

Search result	Not English	Irrelevant	Remining
99	2	30	**67**

In Stage 2, screening was performed to remove duplicated publications, books, and publications not written in English. This reduced the number of publications to 99.

In Stage 3, eligibility of the papers was checked by reading their title and abstract; thus, irreverent papers were discarded. Finally, 67 papers were included in the detailed review in Stage 4...

In Stage 4, the indicators identified from the review papers were classified into four main groups (economical, environmental, health and safety and users' perspective) (Table 2.10). In addition, some examples of statutory orders are proposed from reviewing additional information and materials regarding the improvement in health and safety aspects for building retrofit.

Table 2.10 KPIs identified from literature

Economic Indicators (16 indicators)	
1.	Payback Period (PB)
2.	Return On Investment (ROI)
3.	Internal rate of return (IRR)
4.	Net present value (NPV)
5.	Weighted Average Cost of Capital (WACC)
6.	Annual Energy Cost savings (dollars)
7.	Normalized investment cost (dollars per meter square)
8.	Investment cost (dollars)
9.	Retrofit and operation costs (dollars)
10.	Global Cost (GC) (dollars per meter square)
11.	Revocability Cost (dollars)
12.	Net Cash Flow (NCF) (dollars per year)
13.	Life Cycle Cost (LCC) (dollars)
14.	Profit (dollars)
15.	Peak demand savings (dollars)
16.	Mean cost of intervention saved (dollars per kWh)
Environmental Indicators (26 indicators)	
1.	Percentage of reduction in carbon emissions (%)
2.	Reduction in carbon emissions (tones per year))
3.	Total greenhouses reduced (Mt of CO_2-eq)
4.	Total carbon dioxide emission (g or tones)
5.	Annual emissions global warming potential (kg CO_2-eq)
6.	Annual carbon dioxide emission (kgCO_2/year)
7.	Carbon emission index (kgCO_2/m^2-year)
8.	Greenhouse gas emission (kgCO_2-eq/m^2)
9.	Annual greenhouse gas emission (kgCO_2-eq/m^2)
10.	Emission class indices
11.	Carbon dioxide emission payback periods
12.	Energy payback periods
13.	Reduction of electrical peak demand (%)
14.	Percentage of energy saving (%)
15.	Energy saving (kWh or tones or W or PJ)

Environmental Indicators (26 indicators)	
16.	Annual energy use savings (GWh per year or kWh per year)
17.	Normalized energy savings (kWh/m^2 or W/m^2h)
18.	Normalized annual energy savings (kWh/m^2year)
19.	Percentage of energy generation (%)
20.	Annual energy consumption (kWh/year)
21.	Annual normalized energy consumption (kWh/m^2year or kWh/m^2month)
22.	Energy consumption (kWh or GJ)
23.	Normalized energy consumption (kWh/m^2)
24.	Total site energy (GJ)
25.	Energy consumption class
26.	Life Cycle Analysis (LCA)
Health and Safety (8 indicators)	
1.	Target % in removal of statutory orders
2.	Target % in reduction of number of accidents per year
3.	Target % in reduction of number of legal cases per year
4.	Target % in reduction in number of compensation cases per year
5.	Target % in reduction in amount of compensation paid per year
6.	Target % in reduction in number of health and safety complaints per year
7.	Target % in reduction in number of lost workdays per year
8.	Target % in reduction in number of incidents of specific disease per year
Users' Perspective (12 indicators)	
1.	Predicted Mean Vote (PMV) index
2.	Predicted Percentage of Dissatisfied (PPD) (%)
3.	Indoor air temperature (^oC)
4.	Percentage of discomfort hours in summer (%)
5.	Thermal comfort level
6.	Ventilation and infiltration rates (h-1)/ fresh air volume effect (1/s)
7.	Indoor CO_2 levels (ppm)/other harmful substances
8.	Internal air quality
9.	Work productivity
10.	Workforce performance (dollars/m^2)
11.	Work plane illuminance (lux)
12.	Equivalent continuous weighted sound pressure level (dBA)

As mentioned in Table 2.10, a total of 62 indicators were identified as applicable for measuring the performance of retrofit work. As some of these indicators bear the same meaning, they were further consolidated and presented in Section 2.8 - Definition of retrofit indicators after consolidation".

On the other hand, the reviewed articles were studied and grouped according to:

- Investigation focus (e.g. environmental aspect, economic aspect, users' perspective, health and safety);
- Evaluated retrofit measures (e.g. building envelope, HVAC, lighting, renewable energy, plumbing and drainage etc.);
- Building types (e.g. commercial buildings, residential, hotel, educational building) and origin;
- Data collection methods (e.g. data type and methods to collect them);
- Evaluation methods (e.g. simulation)

2.6 Characteristics of the papers obtained/collected

2.6.1 Investigation focus

Among the 67 journal papers, the indicators for building retrofits were mostly belonged to environmental (52 papers) and economic (43 papers) aspects (Figure 2.5). Also, the previous studies often emphasized on improvement on the indoor environment (12 papers), for example, improvements of wellbeing of occupants, thermal comfort, visual comfort, acoustic comfort, IAQ and degree of satisfaction. Seven papers (Table 2.11) were related to software, calibration or methodology demonstration (Albatici *et al*., 2016, Heo *et al*., 2012, McArthur and Jofeh, 2016, Zhao *et al*., 2009a,). There were also review and discussion papers regarding to energy retrofit toolkits (Lee *et al*., 2015) and promoting heat metering and energy efficiency retrofit in China in "the 12th Five-Year Plan" period (Bao *et al.*, 2012). Some other articles also covered other issues such as the policy (Copiello *et al.*, 2017), social (e.g. productivity) and health and safety aspect (e.g. workforce performance by health year life loss) (Bleyl *et al.*, 2019).

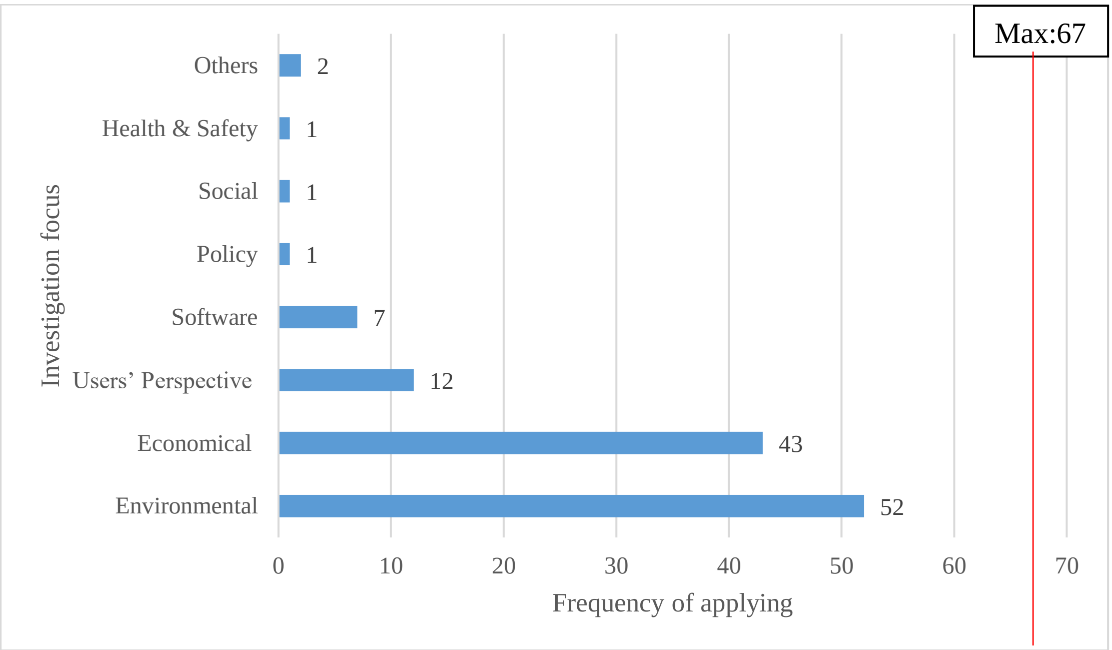

Figure 2.5 Investigation focus in literature review

Table 2.11. Investigation focus in literature review

Investigation focus (No. of articles)	References
Users' Perspective (12)	(Ascione *et al.*, 2017; Fernandes *et al.*, 2018; Hall *et al.*, 2013; Jankovic, 2019; Liu *et al.*, 2015; McArthur and Jofeh, 2016; Roberti *et al.*, 2017; Rocchi *et al.*, 2018; Rodrigues and Freire, 2017; Silva *et al.*, 2013; Zhao *et al.*, 2009a; Zuhaib *et al.*, 2018)
Software (7)	(Albatici *et al.*, 2016; Ascione *et al.*, 2017; Deb and Lee, 2018; Heo *et al.*, 2012; Hong *et al.*, 2015; McArthur and Jofeh, 2016; Wang *et al.*, 2014; Zhao *et al.*, 2009a)
Policy (1)	(Copiello *et al.*, 2017)
Social (1)	(Bleyl *et al.*, 2019)
Health & Safety (1)	(Bleyl *et al.*, 2019)
Others (2)	(Bao *et al.*, 2012; Lee *et al.*, 2015; Raslanas *et al.*, 2011)

Table 2.11. Investigation focus in literature review (Con't)

Aspect (No. of articles)	References
Environmental (52)	(Afshari *et al*., 2014; Aghamolaei, 2019; Albatici *et al*., 2016; Antipova *et al*., 2014; Asaee *et al*., 2017; Ascione *et al*., 2017; Bleyl *et al*., 2019; Cellura *et al*., 2013; Cetiner and Edis, 2014; Ciulla *et al*., 2016; Dall'O *et al*., 2012; de Santoli *et al*., 2014; De Tommasi *et al*., 2018; Deb and Lee, 2018; Dodoo *et al*., 2017; Fernandes *et al*., 2018; Gugul *et al*., 2018; Hall *et al*., 2013; Henriques *et al*., 2015; Huang *et al*., 2012; Jankovic, 2019; Krarti, 2015; Leal *et al*., 2015; Liu *et al*., 2015; Liu *et al*., 2018; Luddeni *et al*., 2018; Mantha *et al*., 2018; McArthur and Jofeh, 2016; McGrath *et al*., 2013; Paiho *et al*., 2015; Peng *et al*., 2014; Pombo *et al*., 2016;Roberti *et al*., 2017; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Shao *et al*., 2014; Silva *et al*., 2013; Silvero *et al*., 2019; Song *et al*., 2017; Tadeu *et al*., 2015; Techato *et al*., 2009; Teres-Zubiaga *et al*., 2015; Touchie and Pressnail, 2014; Wang and Holmberg, 2015; Wang *et al*., 2015; Ward and Choudhary, 2014; Wilkinson, 2012; Xing *et al*., 2015; Xu *et al*., 2016; Zhao *et al*., 2009a; Zheng and Lai, 2018)
Economical (43)	(Afshari *et al*., 2014; Albatici *et al*., 2016; Antipova *et al*., 2014; Asaee *et al*., 2017; Cellura *et al*., 2013; Cetiner and Edis, 2014; Cetiner and Metin, 2017; Ciulla *et al*., 2016; Copiello *et al*., 2017; Dall'O *et al*., 2012; de Santoli *et al*., 2014; Fernandes *et al*., 2018; Ferrari and Beccali, 2017; Gugul *et al*., 2018; Henriques *et al*., 2015; Heo *et al*., 2012; Jankovic, 2019; Kumbaroglu and Madlener, 2012; Leal *et al*., 2015; Liu *et al*., 2018; Luddeni *et al*., 2018; Mantha *et al*., 2018; McArthur and Jofeh, 2016; McGrath *et al*., 2013; Menicou *et al*., 2015; Oree *et al*., 2016; Pombo *et al*., 2016; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Shao *et al*., 2014; Song *et al*., 2017; Tadeu *et al*., 2015; Tadeu *et al*., 2018; Techato *et al*., 2009; Teres-Zubiaga *et al*., 2015; Tokede *et al*., 2018; Valdiserri and Biserni, 2016; Wang and Holmberg, 2015; Wilkinson, 2012; Xu *et al*., 2016; Zhao *et al*., 2009; Zheng and Lai, 2018)

2.6.2 Evaluated retrofit measures

Various kind of retrofit measures were adopted including improvement on building envelope, HVAC, lighting, equipment retrofits, renewable energy, control systems and plumbing and drainage system. Their number of application from the 67 review papers were as follows (Figure 2.6 and Table 2.12):

(1) Building envelope: It was most frequently applied in many cases (56 articles). Different scenarios (low, medium, and high energy) were simulated to evaluate the effect on building envelope, HVAC, lighting and water heating system respectively (Leal *et al*., 2015).

(2) HVAC (31 articles, including natural ventilation (Fernandes *et al*., 2018);

(3) Lighting (16 articles);

(4) Equipment retrofit (15 articles, such as plug loads (Hong *et al*., 2015), all-electric office equipment (Luddeni *et al*., 2018), thermal trap (Wang *et al*., 2014) and thermostatic valve control installation (Zuhaib *et al*., 2018), replacement of chiller (Afshari *et al*., 2014) and more energy efficient appliances e.g. the substitution of CRT (cathode ray tubes and computer monitors for TFT (thin film transistor) monitors (Silva *et al*., 2013). A Water-Source Heat Pump (WSHP) and a two-stage system were installed for utilizing geothermal water system, incorporating the WSHP for heating (Xing *et al*., 2015). It also replaced the constant frequency pumps with variable pumps, including pumps for chilled water, cooling water, and domestic hot water.

(5) Renewable energy (17 articles) (Aghamolaei, 2019; Albatici *et al*., 2016; Asaee *et al*., 2017; Ascione *et al*., 2017; Ferrari and Beccali, 2017; Gugul *et*

al., 2018; Leal *et al*., 2015; McArthur and Jofeh, 2016; McGrath *et al*., 2013; Oree *et al*., 2016; Tokede *et al*., 2018), solar domestic hot water (Cellura *et al*., 2013, Gugul *et al*., 2018), ground source heat pumps (Gugul *et al*., 2018; Ruparathna *et al*., 2017) and wind turbine (Leal *et al*., 2015).

(6) Control system (7 articles, including motion sensor (Wang *et al*., 2014)), daylight control/sensors (Fernandes *et al*., 2018; Ferrari and Beccali, 2017; Luddeni *et al*., 2018) or temperature sensor (Liu *et al*., 2018), energy management and building control system (Tokede *et al*., 2018) and central control and monitoring system for the chiller plant (Zheng and Lai, 2018).

(7) Plumbing and drainage (4 articles, such as alternative heating and domestic hot water (DHW) systems (Tadeu *et al*., 2015), using geothermal water to provide DHW (Xing *et al*., 2015), evaluate the water heating system with different scenarios of energy demand (Leal *et al*., 2015).

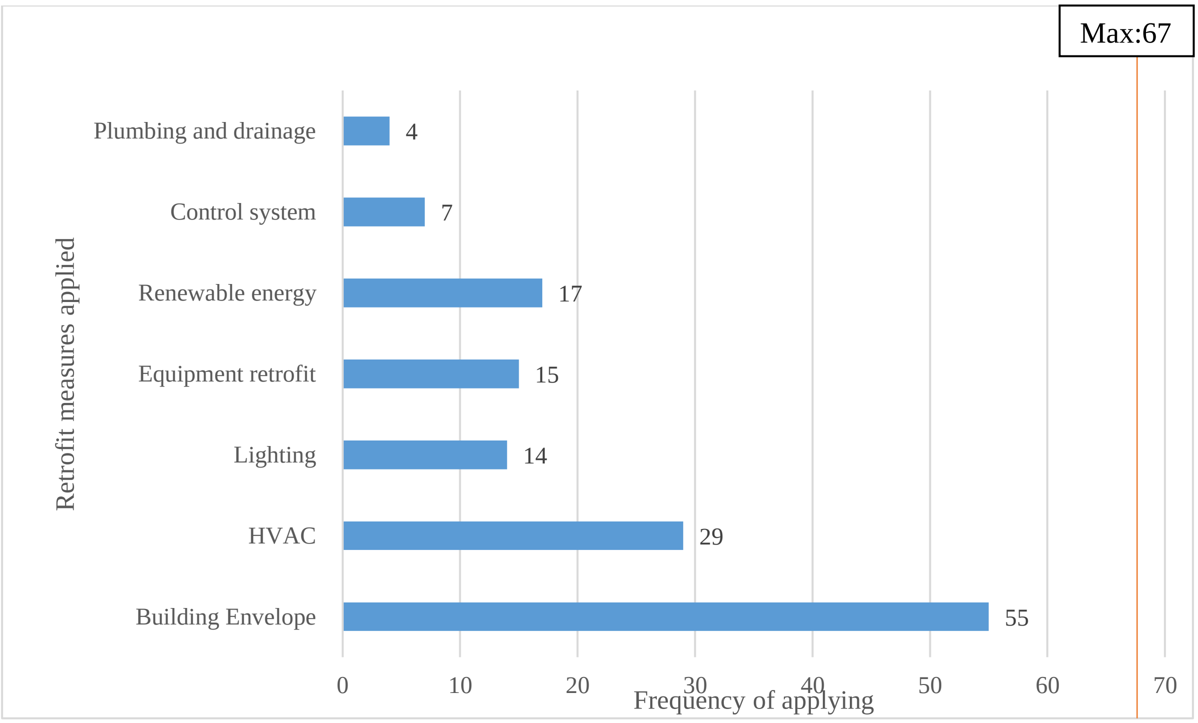

Figure 2.6 Retrofit measures applied in literature review

Table 2.12 Retrofit measures applied in literature review

Retrofit Measures (No. of articles)	References
1. Building Envelope (55)	(Afshari *et al*., 2014; Aghamolaei, 2019; Albatici *et al*., 2016; Antipova *et al*., 2014; Ascione *et al*., 2017; Bleyl *et al*., 2019; Cellura *et al*., 2013; Cetiner and Edis, 2014; Cetiner and Metin, 2017; Ciulla *et al*., 2016; Copiello *et al*., 2017; Dall'O *et al*., 2012; de Santoli *et al*., 2014; Dodoo *et al*., 2017; Fernandes *et al*., 2018; Ferrari and Beccali, 2017; Gugul *et al*., 2018; Hall *et al*., 2013; Henriques *et al*., 2015;Heo *et al*., 2012; Huang *et al*., 2012; Jankovic, 2019; Johansson *et al*., 2016; Krarti, 2015; Kumbaroglu and Madlener, 2012; Leal *et al*., 2015; Liu *et al*., 2015; Liu *et al*., 2018; Luddeni *et al*., 2018;Mantha *et al*., 2018; McArthur and Jofeh, 2016; Menicou *et al*., 2015; Oree *et al*.,2016; Paiho *et al*., 2015; Peng *et al*., 2014; Pombo *et al*., 2016; Roberti *et al*., 2017; Rocchi *et al*., 2018; Rodrigues and Freire, 2017; Ruparathna *et al*., 2017; Shao *et al*., 2014; Silva *et al*., 2013; Silvero *et al*., 2019; Song *et al*., 2017; Tadeu *et al*., 2015; Tadeu *et al*., 2018; Teres-Zubiaga *et al*., 2015; Tokede *et al*., 2018; Valdiserri and Biserni, 2016; Wang and Holmberg, 2015; Wang *et al*., 2015; Ward and Choudhary, 2014; Wilkinson, 2012; Xu *et al*., 2016; Zuhaib *et al*., 2018)
2. HVAC (29)	(Albatici *et al*., 2016; Ascione *et al*., 2017; Bleyl *et al*., 2019; Copiello *et al*., 2017; de Santoli *et al*., 2014; De Tommasi *et al*., 2018; Dodoo *et al*., 2017; Fernandes *et al*., 2018; Ferrari and Beccali, 2017; Hall *et al*., 2013; Hong *et al*., 2015; Krarti, 2015; Leal *et al*., 2015; Liu *et al*., 2015; Liu *et al*., 2018; Luddeni *et al*., 2018; Oree *et al*., 2016; Peng *et al*., 2014; Roberti *et al*., 2017; Rodrigues and Freire, 2017; Shao *et al*., 2014; Silva *et al*., 2013; Tadeu *et al*., 2018; Techato *et al*., 2009; Touchie and Pressnail, 2014; Valdiserri and Biserni, 2016; Wang and Holmberg, 2015; Wang *et al*., 2014; Wang *et al*., 2015; Wilkinson, 2012; Xing *et al*., 2015; Xu *et al*., 2016; Zheng and Lai, 2018; Zuhaib *et al*., 2018)
3. Lighting (14)	(Aghamolaei, 2019; Bleyl *et al*., 2019; Ferrari and Beccali, 2017; Hong *et al*., 2015; Krarti, 2015; Leal *et al*., 2015; Luddeni *et al*., 2018; McArthur and Jofeh, 2016; Peng *et al*., 2014; Silva *et al*., 2013; Techato *et al*., 2009; Wang and Holmberg, 2015; Wang *et al*., 2014; Wang *et al*., 2015; Wilkinson, 2012; Xu *et al*., 2016)

Table 2.12 Retrofit measures applied in literature review (Cont')

Retrofit Measures (No. of articles)	Description	References
4. Equipment retrofit (15)	Plug load	(Hong *et al*., 2015)
	Boiler or heat pump	(Cellura *et al*., 2013; Kumbaroglu and Madlener, 2012; Ward and Choudhary, 2014; McArthur and Jofeh, 2016; Xing *et al*., 2015)
	Distribution system (variable frequency drives are used in pumps)	(Xu *et al*., 2016)
	All-electric office equipment	(Luddeni *et al*., 2018)
	Appliances applied (low, medium, high energy)	(Leal *et al*., 2015)
	Adding valves	(Liu *et al*., 2018), (Zuhaib *et al*., 2018)
	Adding thermal trap	(Wang *et al*., 2014)
	Circulation pump and thermostatic valve controls installation	(Wang *et al*., 2015)
	Replacement of the air conditioning equipment (e.g. chiller)	(Afshari *et al*., 2014)
	Applied more energy efficient appliances, e.g. the substitution of cathode ray tubes, computer monitors for thin film transistor	(Silva *et al*., 2013)
5. Renewable energy (17)	Building integrated photovoltaic/thermal (BIPV/T) system	(Asaee *et al*., 2017; Leal *et al*., 2015)
	Photovoltaic (PV)	(Aghamolaei, 2019; Albatici *et al*., 2016; Antipova *et al*., 2014; Asaee *et al*., 2017; Ascione *et al*., 2017; Ferrari and Beccali, 2017; Gugul *et al*., 2018; Leal *et al*., 2015; McArthur and Jofeh, 2016; McGrath *et al*., 2013; Oree *et al*., 2016; Tokede *et al*., 2018)
	Solar domestic hot water	(Cellura *et al*., 2013; Gugul *et al*., 2018)
	Ground source heat pumps	(Gugul *et al*., 2018; Ruparathna *et al*., 2017)
	Wind turbine	(Leal *et al*., 2015)

Table 2.12 Retrofit measures applied in literature review (Cont')

Retrofit Measures (No. of articles)	Description	References
6. Control system (7)	Motion sensor	(Wang *et al*., 2014)
	Temperature sensor	(Liu *et al*., 2018)
	Daylight control/sensors (e.g. dimmers, sensors and automation system)	(Fernandes *et al*., 2018; Ferrari and Beccali, 2017; Luddeni *et al*., 2018)
	Energy management and building control system (daylighting)	(Tokede *et al*., 2018)
	Central control and monitoring system for the chiller plant	(Zheng and Lai, 2018)
7. Plumbing and drainage (4)	Use of alternative heating and domestic hot water (DHW) systems	(Tadeu *et al*., 2015)
	Use geothermal water to provide DHW	(Xing *et al*., 2015)
	Water heating system in different scenario (low, medium, high energy)	(Leal *et al*., 2015)
	Decrease water consumption through sustainable retrofit	(Wilkinson, 2012).

2.6.3 Building type and origin

The evaluated buildings in literature review were covered with various countries as shown in Table 2.13.

Table 2.13. Origins of the reviewed papers

Countries (No. of articles)	
Italy (12) (Ascione *et al*., 2017; Cellura *et al*., 2013; Ciulla *et al*., 2016; Copiello *et al*., 2017; Dall'O *et al*., 2012; de Santoli *et al*., 2014; Ferrari and Beccali, 2017; Luddeni *et al*., 2018; Roberti *et al*., 2017; Rocchi *et al*., 2018; Valdiserri and Biserni, 2016)	**China (8)** (Peng *et al*., 2014; Huang *et al*., 2012; Liu *et al*., 2018; Song *et al*., 2017; Xing *et al*., 2015; Xu *et al*., 2016; Zhao *et al*., 2009a; Zheng and Lai, 2018)
Sweden (5) (Dodoo *et al*., 2017; Johansson *et al*., 2016; Liu *et al*., 2015; Wang *et al*., 2015; Wang and Holmberg, 2015)	**UK (6)** (Hall *et al*., 2013; Heo *et al*., 2012; Jankovic, 2019; McGrath *et al*., 2013; Tokede *et al*., 2018; Ward and Choudhary, 2014)
Canada (4) (Asaee *et al*., 2017; McArthur and Jofeh, 2016; Ruparathna *et al*., 2017; Touchie and Pressnail, 2014)	**Turkey (3)** (Cetiner and Edis, 2014; Cetiner and Metin, 2017; Gugul *et al*., 2018)
Germany (2) (Kumbaroglu and Madlener, 2012; Shao *et al*., 2014)	**Spain (2)** (Pombo *et al*., 2016; Teres-Zubiaga *et al*., 2015)
US (2) (Hong ***et*** *al*., 2015; Mantha *et al*., 2018)	**Australia (1)** (Wilkinson, 2012)
Brazil (1) (Fernandes *et al*., 2018)	**Cyprus (1)** (Menicou *et al*., 2015)
Finland (1) (Paiho *et al*., 2015)	**India (1)** (Oree *et al*., 2016)
Ireland (1) (Zuhaib *et al*., 2018)	**Lithuania (1)** (Raslanas *et al*., 2011)
Paraguay (1) (Silvero *et al*., 2019)	**Russia (1)** (Paiho *et al*., 2015)
Singapore (1) (Deb and Lee, 2018)	**South Africa (1)** (Wang *et al*., 2014)
Thailand (Techato *et al*., 2009)	**United Abu Dhabi (1)** (Afshari *et al*., 2014)
Yazd (1) (Aghamolaei, 2019)	

Among the 67 reviewed papers (Figure 2.7 and Table 2.14), retrofit performance evaluations were frequently performed in residential buildings (e.g. two historical residential buildings (Ciulla *et al*., 2016; Rodrigues and Freire, 2017) and commercial buildings (e.g. mixed-use office (Afshari *et al*., 2014), historical buildings with office and stores (Xu *et al*., 2016), and hotel (Xing *et al*., 2015)).

Retrofit performance evaluation were also performed in other type of buildings such as glasshouses (Ward and Choudhary, 2014), farmhouse (Rocchi *et al*., 2018), laboratory (Ward and Choudhary, 2014) and university campus (de Santoli *et al*., 2014; Fernandes *et al*., 2018; Huang *et al*., 2012; Mantha *et al*., 2018; McArthur and Jofeh, 2016; Zuhaib *et al*., 2018).

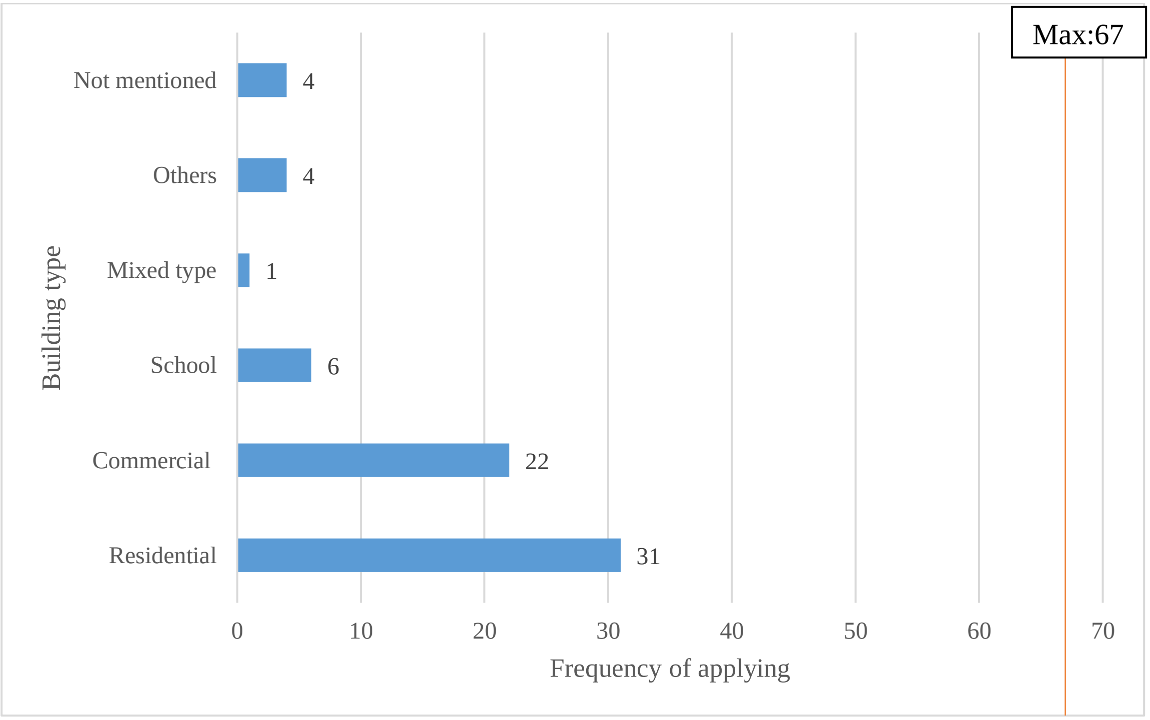

Figure 2.7 Building types in the literature review

Table 2.14 Building types in the literature review

Building Type
1. Residential (e.g. apartment, single house, mixed-use) (31) (Aghamolaei, 2019; Albatici *et al*., 2016; Antipova *et al*., 2014; Asaee *et al*., 2017; Cetiner and Edis, 2014; Cetiner and Metin, 2017; Ciulla *et al*., 2016; Copiello *et al*., 2017; Dall'O *et al*., 2012; Dodoo *et al*., 2017; Gugul *et al*., 2018; Hall *et al*., 2013; Jankovic, 2019; Johansson *et al*., 2016; Krarti, 2015; Leal *et al*., 2015; Liu *et al*., 2015; Liu *et al*., 2018; McGrath *et al*., 2013; Menicou *et al*., 2015; Paiho *et al*., 2015; Pombo *et al*., 2016; Raslanas *et al*., 2011; Rodrigues and Freire, 2017; Silvero *et al*., 2019; Tadeu *et al*., 2018; Teres-Zubiaga *et al*., 2015; Touchie and Pressnail, 2014; Wang and Holmberg, 2015; Wang *et al*., 2015; Xu *et al*., 2016; Zhao *et al*., 2009a)
2. Commercial (e.g. office, historical office and store, hotel) (22) (Afshari *et al*., 2014; Ascione *et al*., 2017; Bleyl *et al*., 2019; De Tommasi *et al*., 2018; Deb and Lee, 2018; Ferrari and Beccali, 2017; Heo *et al*., 2012; Hong *et al*., 2015; Kumbaroglu and Madlener, 2012; Luddeni *et al*., 2018; McArthur and Jofeh, 2016; Oree *et al*., 2016; Peng *et al*., 2014; Ruparathna *et al*., 2017; Shao *et al*., 2014; Silva *et al*., 2013; Song *et al*., 2017; Tokede *et al*., 2018; Valdiserri and Biserni, 2016; Wilkinson, 2012; Xing *et al*., 2015; Xu *et al*., 2016; Zheng and Lai, 2018)
3. Campus/University (6) (de Santoli *et al*., 2014; Fernandes *et al*., 2018; Huang *et al*., 2012; Mantha *et al*., 2018; McArthur and Jofeh, 2016; Zuhaib *et al*., 2018)
4. Glasshouses (1) (Ward and Choudhary, 2014)
5. Farmhouse (1) (Rocchi *et al*., 2018)
6. Historical (1) (Roberti *et al*., 2017)
7. Research laboratory (1) (Ward and Choudhary, 2014)
8. Residential + Commercial (1) (Xu *et al*., 2016)
9. Not mentioned or all types (4) (Cellura *et al*., 2013; Henriques *et al*., 2015; Techato *et al*., 2009; Wang *et al*., 2014)

2.7 Data collection methods

" Research methodology is a strategic plan of action, whereas research methods are the techniques used in research." (Groenland and Dana, 2020, p.163). Details of exploration of the common data collection methods can be found in various qualitative textbooks (Groenland and Dana, 2020). A mix of the data collection methods may be used.

Among the reviewed papers on evaluating building retrofits performance, the data collection methods included:

(A) Interviews (Table 2.9)

(B) Questionnaires and surveys (Table 2.10)

(C) Inspection/site visit/ audit (Table 2.11)

(D) On-site measurement and experiment (Table 2.12)

(E) Monitored data (in-house or from weather station) (Table 2.13)

(F) From energy supplier/manufacturer/owner records/bill of quantities (Table 2.14)

(G) From standard/regulation/code/law (Table 2.15)

(H) From literature papers or other website/sources (Table 2.16-Table 2.17)

(I) Data retrieval from databases/simulations (Table2.21)

(J) Unspecified method (Table 2.19)

The type of data collected from literature review can be classified into:

(i) Energy consumption/saving – e.g. energy, electricity and natural gas consumption

(ii) Cost data – e.g. the utility bill, cost for retrofit alternatives and discount rate

(iii) Indoor parameter – e.g. indoor air temperature, humidity ratio, CO_2 generation rate

(iv) Information related to construction and equipment – e.g. building operation schedule and equipment loads

(v) Occupant – e.g. comfort condition, complaints of occupants and users' experience

(vi) External condition – e.g. outdoor environmental condition and solar irradiation

(vii) Others – not specifical described

2.7.1 Interviews (individual or group)

There can be individual or group interviews. Interviews may be structured, semi-structured or unstructured (Robson, 2011). "A structured one can be similar the questionnaire type approach to yield a fairly superficial level of response. The semi-structured interviews include number of pre-determined areas of interest with possible prompts to help guide the conversation. Unstructured interviews can discuss a broad area while the researcher largely follows the direction of the participant".

Interviews usually take between 30 to 90 minutes to complete and audio-taped can be used for later transcription. "In-depth interviewing is a qualitative research technique that involves conducting intensive individual interviews with a small number of respondents to explore their perspectives on a particular idea, program, or situation." (Boyca and Neale, 2006).

Individual interviews can be useful for researcher to explore in-depth the experiences or view of participants. It can be conducted in various forms such as face to face, by telephone or web-based approach (Petty, 2020). Through paper forms, the information can be entered directly or transcribed. One of the advantages of paper is its low costs for initial creation, and no technology was used and flexible enough to fit the workflow of the qualitative interview process. It is also portable, and as such interviews can be done at the most convenient location (e.g. site, office or home). After completion, data collected from the qualitative interviews on paper forms can be transferred into electronic one for easier storage and analyzing purpose in future stage. However, paper forms can have its disadvantages in obtaining and managing data when collecting community survey. For web-based forms, it is a more flexible method where the forms can be adjusted easily with moderate effort by the form designer. The disadvantage of web-based forms was not as easy to use as paper-based method, and generally not portable (Wilcox *et al*., 2012).

For a group interview, six to ten individuals can be grouped and discuss on a particular topic (Petty, 2020). Three or four subgroups may also be formed, with eight to twelve participants in a group session (Groenland, 2020). Depending on the nature of research, the focus group can be homogenous or heterogeneous (with similar or different experience, background, or position). It usually lasts for one to two hours. The discussion is usually facilitated by the researcher. During the discussion, a second person can help to manage any issues that arise (e.g., someone need to leave early, take notes of some non-verbal observation, assist the communication, and supports the researcher in reflecting and debriefing). Audio-taped may also be used for transcription afterwards. This process allows an efficient way to acquire range of rich data on a particular issue and requires skillful facilitation to manage the dynamic of the group discussion to ensure all opinions are heard (Petty, 2020). It also provides critical information on developing hypotheses or interpretation of quantitative data (Groenland, 2020). Primary data collection for building evaluation from interviews were shown in Table 2.15.

<u>Data collection methods applied in the reviewed papers</u>

Table 2.15: Data collection methods – interview

Method	Categories	Details	References
Interviews	Energy consumption/saving	Monthly energy end-uses	Zheng and Lai (2018)
		Useful information on the usage pattern (e.g. use of lighting, equipment and AC systems, occupancy in various rooms.)	Oree *et al*. (2016)
	Cost data	Cost data associated with retrofit alternatives	Ruparathna *et al*., (2017); Zheng and Lai, (2018)
	Indoor parameters	Thermal comfort of the occupants and any defects they noticed in building	Oree *et al*. (2016)
	Information related to construction and equipment	Physical characteristics of the buildings (e.g. age, number of floors, floor areas)	Zheng and Lai, (2018)
		(i) Thermal properties of construction materials (e.g. thermal transmittance, emissivity, solar absorptance); (ii) dynamic heat capacity of the building envelope; (iii) internal loads (plug-in appliances, lighting, occupants, etc.); (iv) properties of the heating system and (v) external environment (weather data)	Heo *et al*., (2012)
		Types of thermal insulation materials, window frames and their application methods	Cetiner and Metin, (2017)
		Conservation score if a certain energy saving measures is implemented (Occupants were asked to fill out individually the pairwise comparison matrix.)	Roberti *et al*., (2017)
		The previous energy-intensive lighting system in the main building and conference center was replaced in 2008 with energy-saving LED units was noted. Furthermore, a large proportion of the hotel' sold equipment had been gradually updated.	Xing *et al*., (2015)

2.7.2 Questionnaires and surveys

Questionnaires can be applied in wide variety, from determining small opinion, gathering information of public perception, analysis quantitative options, to develop a user interface tool. Survey is a specific type of questionnaire that only some opinions or belief are analyzed to make them appropriate for collecting information about occupant' perception of comfort in a building (Stawarski and Phillips, 2008). For example, an online survey tool called "Comfortmeter" can objectify the subjective comfort experience of building occupants on six aspects. It includes thermal comfort, air quality, acoustics, lighting, individual control, and office environment and cleanliness, and their work performance impact of working environment and personal characteristics (Bleyl *et al*., 2019). The overall comfort score can increase two to four percent for a successful deep energy retrofit of a low performance building (Coolen *et al*., 2012). The primary data collection for building evaluation from questionnaires or surveys were shown in Table 2.16.

2.7.3 Observation

It can be a formal schedule of pre-determined areas to notice, or informal one that decides by personnel to observe what to attend to. Data may be collected by various methods including field notes, audiotape, and videotape. Observation can be a time-consuming process that lasting months or years. The observer usually writes a description of what have been observed and explained what is going on in that situation by the help of theoretical framework on a particular issue. The advantage of this method over interview method is the ability to observe theory-in-action rather than just supporting theory (Petty, 2020). Table 2.17 shows the details of data collection methods for inspection, site visit or audit:

Table 2.16: Survey and questionnaire

Method	Categories	Details	References
Survey	Energy consumption/saving	Annual heating and electric energy consumption values (and randomly surveying the behavior of the apartment occupants.)	Albatici *et al*. (2016)
		Energy saving/costs.	Jankovic (2019)
		Energy demand or consumption behavior of the occupants	Fernandes *et al*. (2018); Gugul *et al*. (2018)
	Indoor parameters	Dry bulb temperature, humidity ratio.	Fernandes *et al*. (2018)
	Information related to construction and equipment	Characteristics of their buildings and implemented energy saving measures	Zheng and Lai (2018)
		Socio-economic characteristics and construction details of the dwelling, space and domestic hot water heating equipment, lighting and appliances, and heat gain sources	Gugul *et al*. (2018)
	Occupant	Workforce performance	Bleyl *et al*. (2019)
		Occupants' satisfaction with thermal comfort, visual comfort, acoustic comfort and indoor air quality	Zuhaib *et al*. (2018)
Questionnaires	Occupant	User experience	Jankovic (2019)
		To assess occupants' main complaints to obtain a subjective appraisal of the IEQ and help identifying the most important IEQ-related problems present in the building. (Besides questions related to age, gender, metabolic activity, clothes and characteristics of the offices, number of occupants, position related to the windows, identification of appliances and systems and patterns of use, the occupants were asked to identify the three most relevant aspects for their comfort conditions (thermal, acoustic and visual comfort, ventilation conditions and IAQ).	Silva *et al*. (2013)
		Calculate PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) (to investigate how the households from non-retrofitted and retrofitted buildings experience the indoor environment.)	Liu *et al*., (2015)

Table 2.17 Data collection methods -inspection/site visit/audit

Method	Categories	Details	References
Inspection/Site visit/audit	Energy consumption/saving	Energy consumption of electrical tools used during the construction	Cetiner and Metin (2017)
	Cost data	Electricity bills	Oree *et al*. (2016)
	Information related to construction and equipment	(i) Thermal properties of construction materials (e.g. thermal transmittance, emissivity, solar absorptance); (ii) Dynamic heat capacity of the building envelope (iii) Internal loads (plug-in appliances, lighting, occupants, etc.), (iv) Properties of the heating system, (v) Properties describing ventilation and infiltration	Heo *et al*. (2012)
		Activity data (e.g. occupancy schedules and density, metabolic rates, comfort environmental conditions)	Menicou *et al*. (2015)
		Occupancy	Oree *et al*. (2016)
		Heating and cooling set point temperatures, minimum levels of fresh air, desirable lighting levels and equipment loads	Menicou *et al*. (2015)
		All electrical equipment and appliances within the building were identified, their power ratings and estimate their hours of operation (values for the connected loads) were recorded.	Oree *et al*. (2016)
		The compliance of the documentary theoretical data with the actual appearance of the buildings was verified.	Albatici *et al*. (2016)
		Structural and electrical blueprints, thermal performance of building envelope	Oree *et al*. (2016)
		Building related data (visual inspections and photographic)	Wilkinson (2012)
	(Not mention)	(Field survey)	Afshari *et al*. (2014); Cetiner and Edis, (2014)

2.7.4 Monitored data

Although there are no established standards on the frequency that data needs to be collected, the proposed time intervals ranged from 5-15 minutes for real-time monitoring (Xia *et al*., 2014) to over an hour for weather data (Santamouris, 2001). Traditionally, the data for analyzing the efficiency and performance of building systems were manually collected and documented with the help of data logs or data sheets for information. It can be a tedious, time consuming and not entirely accurate approach for data regarding energy use parameters such as hot water, plug loads, and HVAC can be indirectly or directly calculated with the help of installed meters with the respective usage quantities. As such, using sensor networks allow fast transmitting large amounts of data. The wireless one has a lot of advantages than the wired networks in cases of building retrofits. It can save the additional wiring costs (that can be much more than in new installation) and also more convenient for the building occupants (Mantha *et al*., 2016).

Parameters affect building energy consumption or building performance can be classified into static (Figure 2.8) and dynamic parameters (Figure 2.9). For static parameters in a building, it includes (i) primary building information, (ii) building materials, (iii) building orientation, (iv) building zones. For dynamic parameters in a building, it includes (i) weather data, (ii) occupancy data (such as schedule information, occupancy characteristics, occupant comfort information), (iii) energy and water use (such as equipment data, hot water usage, and electricity or natural gas consumption for lighting, plug load and heating and ventilation condition system) (Mantha *et al*., 2016).

Besides the monitoring data, field experiment "is a research study in a realistic situation in which one or more independent variables are manipulated by the experimenter under as carefully controlled conditions as the situation will permit." (Kerlinger, 1986, p.369). Experiment was conducted to find the airtightness levels for each applied airtightness upgrade using the blower door method in accordance with ATTMA TS1 'Measuring Air Permeability of Building Envelopes' (Hall *et al*. 2013).

Figure 2.8 Static parameters in a building (extracted from Mantha *et al*., 2016)

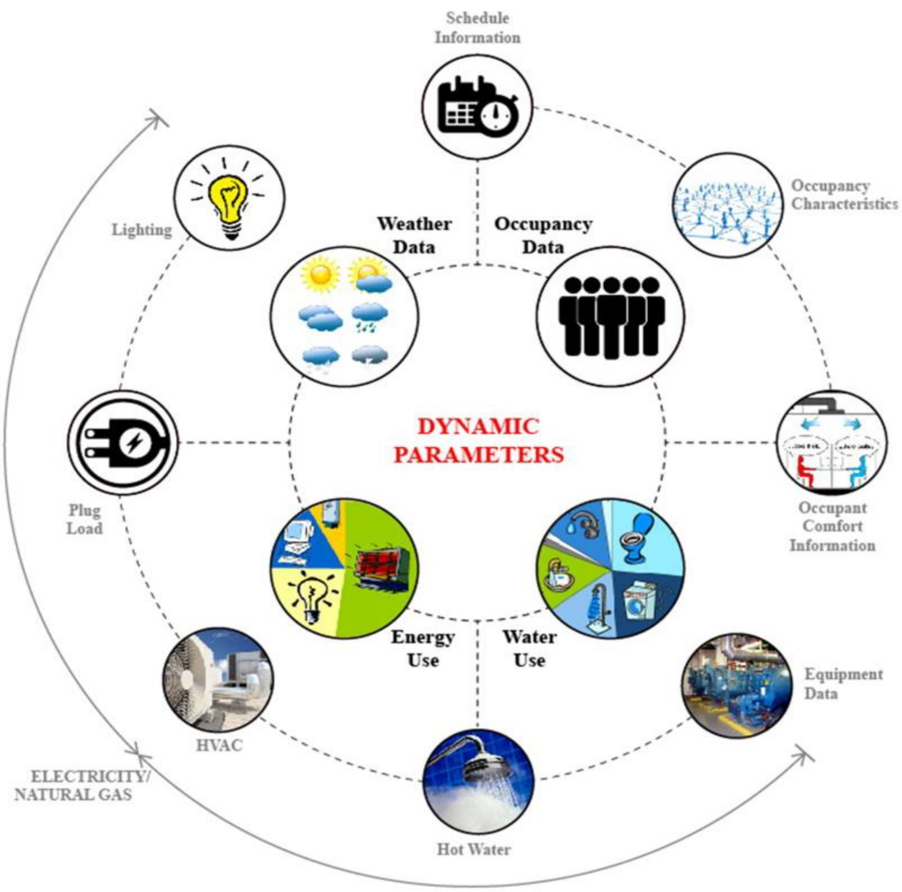

Figure 2.9 Dynamic parameters in a building (extracted from Mantha *et al*., 2016)

Table 2.18 Data collection methods - on-site measurement and experiment

Method	Categories	Details	References
On-site measurement	Energy consumption/saving	Energy consumption/ daily natural gas consumption	Tokede *et al*. (2018)
		DHW consumption	Xing *et al*. (2015)
		Electricity use of household appliances and the whole building	Liu *et al*. (2015)
	Cost data	The utility bill	Song *et al*. (2017)
	Indoor parameters/ Internal condition	Indoor and outdoor temperatures (air temperature next to each heater was also gathered in order to check that all of them were working properly)	Teres-Zubiaga *et al*. (2015)
		lighting levels	Oree *et al*. (2016)
		Internal condition (such as temperature, humidity, and light intensity)	Jankovic (2019); Johansson *et al*. (2016); Mantha *et al*. (2018); Zuhaib *et al*. (2018)
		IAQ conditions – measurement of the concentration of suspended particles (PM_{10}), CO_2, carbon monoxide (CO), O_3, formaldehyde (HCHO) and total VOCs	Silva *et al*. (2013)
		CO_2 concentration	Zuhaib *et al*. (2018)
		Indoor temperature and indoor environment	Liu *et al*. (2015)
	Occupant	Comfort conditions – 1.1) thermal comfort (air temperature (Ta) and speed, direction, and relative humidity (RH), To, black bulb temperature for calculating PMV & PDD), 1.2) acoustic comfort (A-weighted sound pressure level, LA_{eq}) and 1.3) daylight conditions (illuminance level);	Silva *et al*. (2013)
		Thermal comfort	Oree *et al*. (2016)
		Noise level	Zuhaib *et al*. (2018)
	External condition	Outdoor condition (e.g. weather; dry bulb air temperature, relative humidity, barometric pressure, total and diffuse solar irradiation, wind speed, wind direction and rainfall)	Jankovic (2019); Zuhaib *et al*. (2018)

(Cont')

Method	Categories	Details	References
	Information related to construction and equipment	The loads from equipment and lighting	Fernandes *et al*., (2018), Gugul *et al*. (2018)
		Inlet water temperature, outlet chilled water temperature and flow rate of chilled water	Song *et al*. (2017)
		The state of conservation of building (poor, good, excellent), facade materials (i.e., plaster, brick, stone), window materials (frames and glazing) and number of inhabited floors	Dall'O *et al*. (2012)
		Characterization of the operative conditions of the buildings (building air tightness (ACH), occupation patterns, equipment and appliances existing in the rooms and their pattern of use)	Silva *et al*. (2013)
		Actual thermal characteristics and building envelope thermal performance of the buildings (thermal transmittance, U-value, of the building envelope) and geometrical surveying of significant parts of the building	Albatici *et al*. (2016)
		Thermal audit	Zuhaib *et al*. (2018)
		Input parameters of internal loads, HVAC system, schedules of lighting and equipment loads, and occupancy rate (to determine the present lighting and equipment loads.); The temperature of supply and return chiller water, chiller waterflow, and corresponding electricity consumption of the chillers	Xing *et al*. (2015)
		The infiltration rates and electrical heaters heat input	Teres-Zubiaga *et al*., (2015)
Experiment	Information related to construction and equipment	Airtightness levels as indicated by ACH values (determined experimentally for each applied airtightness upgrade using the blower door method in accordance with ATTMA TS1 'Measuring Air Permeability of Building Envelopes')	Hall *et al*., (2013)

Table 2.19 Data collection methods - monitored data

Method	Categories	Details	References
Monitored data (in-house or from weather station)	Energy consumption/saving	Hourly electricity consumption	Gugul *et al*. (2018)
	Indoor parameters/ Internal condition	Temperature	Ward and Choudhary (2014)
	(Not mention)	Field monitoring and laboratory testing to develop model output processor, the data collected were used to determine how the COP would change with the balcony space temperature	Touchie and Pressnail (2014)
	External Condition	Temperature and hourly meteorological data	Menicou *et al*. (2015); Gugul *et al*. (2018)
		Real outdoor environmental conditions recorded	Teres-Zubiaga *et al*. (2015)
		Annual solar irradiance data (from Hong Kong Observatory, plus the glazing parameters of university buildings)	Huang *et al*. (2012)
		Solar heat gains ˚I·S (data obtained from the local climate profile) is calculated based on these data	Wang and Holmberg (2015)

2.7.5 Documentary analysis

Many information and written documents may be taken from articles, notes, minutes of meetings etc., or may also include photographs, drawings, pictures etc. (Petty, 2020). By analyzing these documents, it needs to identify the context of the document, who wrote it and the purpose of these information. They include published or unpublished documents, and can be classified into three essential types: (i) public records (e.g. annual reports, handbooks, newspapers); (ii) personal records (e.g. reflections, daily records, etc.); (iii) physical evidence (e.g. posters, agendas, etc.) (O'Leary, 2014). There are three sources relevant for document analysis including (i) sales records; (ii) institutional records and (iii) personal documents (Webb et. al., 2000). For the building retrofit performance evaluation, the data collection was mainly focusing on institutional records within companies. On the other hand, there can be different types of text (O'Leary, 2014, pp. 245-246) including the following methods (1-6), while type (i) and type (ii) were frequently applied during the building retrofit evaluation.

(i) *Official data and records* (e.g. international and national data, local government data, legislation, policy documents);

(ii) *Organizational communication, documents, and records* (e.g. websites, press releases, meeting agenda and minutes, human resource and client records)

(iii) *Personal communication, documents, and records* (e.g. letters, emails, diaries, mobile phone texts)

(iv) *The media/ contemporary entertainment* (e.g. websites, newspapers, commercials, biographies and autobiographies)

(v) *The arts* (e.g. paintings, drawings, photography, music, films)

(vi) *Social artefacts* (e.g. any products of social beings)

The data collected from Table 2.20 (energy supplier/manufacturer/owner records/bill of quantities) belong to type (ii) - *Organizational communication, documents, and records* of above, while data collected in Table 2.21 (standard/regulation/code/law) belong to type (i) - *Official data and records*. Table 2.22 and Table 2.23 shows the data collection from literature and other websites.

Table 2.20 Data collection methods - from energy supplier/manufacturer/owner records/bill of quantities

Method	Categories	Details	References
Energy supplier	Energy consumption/saving	Gas/electricity/energy consumption	Jankovic (2019); Tokede *et al*. (2018)
		Actual energy consumptions of some selected buildings	Cetiner and Edis (2014)
	Cost data	Energy costs for electricity and natural gas	Tadeu *et al*. (2018)
		Energy prices	Leal *et al*. (2015)
		An average cost of primary energy (natural gas)	Dall'O *et al*. (2012)
Manufacturer's data	Information related to equipment	Typical power ratings; nonlinear efficiency curves and coefficients of performance curves of real products	De Tommasi *et al*. (2018); Ward and Choudhary (2014)
Data retrieval from company/owner records/bills	Energy consumption/saving	Water heating gas/ energy/ electricity consumption data	Afshari *et al*. (2014); Cetiner and Metin (2017); Ruparathna *et al*. (2017); Ward and Choudhary (2014)
		Estimated yearly primary energy saving	Cellura *et al*. (2013)
	Cost data	Cost data (e.g. unit costs of natural gas, electricity, water and fuel for transportation)	Cetiner and Metin (2017); Gugul *et al*. (2018)
		The unit costs for natural gas, electricity, water and gasoline costs respectively	Cetiner and Edis (2014)
		Economic data related to the expenditures incurred for the realization of the retrofit actions	Cellura *et al*. (2013)
	Indoor parameters/ Internal condition	Heating and cooling set point temperatures, minimum levels of fresh air	Ward and Choudhary (2014)
	External condition	Annual solar irradiance data (from Hong Kong Observatory, plus the glazing parameters of university buildings)	Huang *et al*. (2012)

(Cont')

Method	Categories	Details	References
Data retrieval from company/owner records/bills	Information related to construction and equipment	Desirable lighting levels and equipment loads	Gugul *et al*. (2018)
		Fan efficiency	Dodoo *et al*. (2017)
		Testing data of heat supplies	Liu *et al*. (2018)
		Quantities of materials required for each retrofit strategy	Rodrigues and Freire (2017)
		Occupancy schedules and density, metabolic rates, comfort environmental conditions	Menicou *et al*. (2015)
	Others	Reference (virtual) building defined based on information from energy certificates and statistical data)	Tadeu *et al*. (2018)
		Energy audit reports (56 reports) contain detailed analysis of energy distribution and usage by various energy consuming systems in buildings. (Post retrofit information includes overall energy consumption and the improved chiller plant efficiency)	Deb and Lee (2018)
Bill of Quantities	Cost data	Investment cost	Copiello *et al*., (2017); Tokede *et al*. (2018)

Table 2.21 Data collection methods - from standard/regulation/code/law

Method	Categories	Details	References
Standard/ regulation/ code/ law	Cost data	Discount rate	Pombo *et al*. (2016); Rocchi *et al*. (2018)
		The cost-optimal improvement measures were calculated as recommended by the European Commission (Based on Delegated Regulation No. 244)	Tadeu *et al*. (2018)
	Occupant	Prepare occupant surveys for the staff and students	Zuhaib *et al*. (2018)
	Indoor parameters/ Internal condition	Temperature set-point selection	Teres-Zubiaga *et al*. (2015)
	External condition	Weather data/ monthly climatic data	Cetiner and Metin, (2017); Pombo *et al*. (2016)
		The climatic zones, the heating degree days, and the heating periods	Tadeu *et al*. (2018)
	Information related to construction and equipment	Settings for occupancy, office equipment, lighting, and air ventilation/infiltration (with relative reference)	Luddeni *et al*. (2018)
		Degree hours (evaluate comfort on an annual basis)	Rocchi *et al*. (2018)
		The choice of people activity level	Fernandes *et al*. (2018)
		Energy performance certificate data	Gugul *et al*. (2018)
		Three different scopes of carbon emissions associated with building energy use were quantified.	Zheng and Lai (2018)
		HVAC control alterations (modelled to maximize efficiencies)	Tokede *et al*. (2018)

		U-value for the opaque envelope, glass enclosures; heating season and the operational hours	Ciulla *et al*. (2016)
		U-value of envelope	Menicou *et al*. (2015)
		Airtightness levels (as indicated by ACH values)	Hall *et al*. (2013)
		Radiant heat gain before installation of the shading system	Huang *et al*. (2012)

(Cont')

Method	**Categories**	**Details**	**References**
Standard/ regulation/ code/ law		Occupancy density, lighting and equipment load	Xing *et al*. (2015)
		Airtightness of the building, U value of window and ACH	Dodoo *et al*. (2017)
		Material inventory	Wang *et al*. (2015)
		Internal heat gain	Oree *et al*. (2016); Roberti *et al*. (2017)
		The CO_2 emissions factor/ energy conversion factors	Tadeu *et al*. (2015)
		The heating system is switched on (winter period) as prescribed	Valdiserri and Biserni (2016)
		Estimated service life, building life span	Cetiner and Metin (2017)
		Occupant density, the electric load for artificial lighting and office appliance, lighting power density and a time activity, the fresh airflow rate, the efficiencies of each subsystem, primary energy conversion factors, emission factors	Ferrari and Beccali (2017)
		Infiltration rate and internal gains	Teres-Zubiaga *et al*. (2015)
		Infiltration rate (To estimate the uncertainties in model parameters)	Heo *et al*. (2012)
	Others	Refer of other countries code requirement and other developed threshold values in other papers (as no energy code in the studied area)	Silvero *et al*. (2019)

Table 2.22 Data collection methods - from literature papers

Method	Categories	Details	References
Literature papers	Energy consumption/saving	Energy consumption/saving data	De Tommasi *et al*. (2018); Krarti (2015); Liu *et al*. (2018); Paiho *et al*. (2015); Xu *et al*. (2016)
		Refer the energy code requirement of other countries (as no energy code in the studied area)	Silvero *et al*. (2019)
	Cost data	Unit investment costs/ investment cost for retrofit measures	Henriques *et al*. (2015); Luddeni *et al*. (2018); Ruparathna *et al*. (2017)
		Cost of power plant installment	Krarti (2015)
		Price for natural gas/ electric and natural gas tariffs	Gugul *et al*. (2018); Luddeni *et al*. (2018)
		Discount rate/ Nominal interest rates	Gugul *et al*. (2018); deu *et al*. (2018); Wang and Holmberg (2015)
		Payback period, economic lifespan for dwelling (validation of the existing Swedish residential building type for base case data inventory)	Wang and Holmberg (2015)

		Maintenance cost savings	Bleyl *et al*. (2019)
	Occupant	Labor productivity	Bleyl *et al*. (2019)
	External condition	Weather data	Ascione *et al*. (2017); Roberti *et al*. (2017)

(Cont')

Method	Categories	Details	References
Literature papers	Information related to construction and equipment	Quantities of materials required/material selection for retrofit strategy	Hall *et al*. (2013); Rodrigues and Freire (2017)
		Inventory data (for the alternative packages regarding material production and transportation; environmental impact of building materials manufacture (e.g. CO_2 emission coefficient for aluminum)	Huang *et al*. (2012); Tadeu *et al*.(2015)
		Characterization of the building sector	Henriques *et al*. (2015)
		Technical details (e.g. rated efficiency of the gas-fired boiler, typical power ratings of equipment, PV equipment lifetime)	Leal *et al*. (2015); Ward and Choudhary (2014); Xing *et al*. (2015)
		Building model development, performance or uncertainties evaluation	Heo *et al*. (2012); Krarti (2015); Touchie and Pressnail (2014)
		Energy consumption habits	Tadeu *et al*. (2018)
		Prototypical construction features	Krarti (2015)
		Settings for occupancy, office equipment, lighting and building operation schedules	Krarti (2015); Luddeni *et al*. (2018)

		Selection/Availability of the retrofit strategies	Antipova *et al*. (2014); Leal *et al*. (2015)
		Air ventilation/infiltration	Luddeni *et al*. (2018)
		From metered data or factored from similar buildings, hourly heating, cooling, and power demand were estimated	Ward and Choudhary (2014)

Table 2.23 Data collection methods - from other website/sources

Method	Categories	Details	References
Other websites/ sources	Energy consumption/saving	Total building energy consumption &/ variation between years	Cellura *et al*. (2013); Dall'O *et al*. (2012); de Santoli *et al*. (2014)
	Cost data	Inflation rate, discount rate	Tokede *et al*. (2018)
		Energy price/ cost of electricity and natural gas &/ water and gasoline costs	Cetiner and Edis (2014); Tadeu *et al*. (2015); Wang and Holmberg (2015)
		Equipment costs (e.g. PV and wind turbine)	Leal *et al*. (2015)
	External condition	Climate data (downloaded from the EnergyPlus's weather data web site; from US Department of Energy weather files)	Gugul *et al*. (2018); Xu *et al*. (2016)
	Information related to construction and equipment	Construction data and details (e.g. external walls of the dwelling are composed of two layers of hollow bricks separated by an air gap, the indoor surfaces of the walls consist of plaster over gypsum)	Teres-Zubiaga *et al*. (2015)

		Inventory of buildings (containing general information useful to describe the composition in terms of number, type and dimension of buildings; energy label of municipally owned buildings)	de Santoli *et al*. (2014)
		Usually present of central heating system in the detached buildings	Cetiner and Metin (2017)
		Retrofit alternatives (gathered through market search)	Cetiner and Edis (2014)
		Avoided CO_2 emissions attained with each retrofit investment measure/ CO_2 generation rate	Henriques *et al*. (2015) ; Krarti (2015)

2.7.6 Data retrieval from databases/simulations

Field simulation is a qualitative research methodology that "encompasses a set of research methods rather than any single instrument or form. (Salancik 1979, pp. 638)". "The data collected are assumed to be outcroppings of come underlying process and are the stuff from which the structures and processes which generated them are inferred. This naïve realism notion of data assumes that data have no meaning outside of the theories which link to them. (p. 639)".

Among the reviewed papers, some of the data were retrieved from various databases (Table 2.24), for examples:

- Ecoinvent database - includes majority of the materials, fore- ground data related to the main production and assembly processes, as well as background data for transport, electricity and fuel consumption) (Cellura *et al*., 2013; Cetiner and Edis, 2014; McGrath *et al*., 2013; Pombo *et al*., 2016; Rocchi *et al*., 2018; Shao *et al*., 2014; Wang *et al*., 2015);
- Photovoltaic Geographical Information System (PVGIS) - includes measured solar irradiation for European locations and provides PV electricity generation estimates (Luddeni *et al*., 2018);
- DesignBuilder - includes hourly schedules over the year of occupancy, DHW need, lighting and electrical equipment power densities); (Ascione *et al*., 2017);
- Meteonorm database for weather data (Dodoo *et al*., 2017; Valdiserri and Biserni, 2016);
- CYPE database (Pombo *et al*., 2016);
- LEGEP database - contains the description of all elements of a building and their life cycle costs based on the German standard (Federal Ministry of Transport,

Building and Urban Affairs, 2020) that can be mapped to other similar standards (Shao *et al*., 2014);

- Database of Energy Efficiency Performance (DEEP) database - an SQL database and involves input parameters of prototype building models and the simulation results from energy models (Hong *et al*., 2015);
- Low Energy Buildings Database (LEBD) – contains low energy projects (newly builds and retrofits) that can learn about real projects and how they turned out; (McGrath *et al*., 2013)
- Government and other public databases (Afshari *et al*., 2014; Tadeu *et al*., 2018; Wilkinson, 2012)

Table 2.24 Data collection methods - data retrieval from databases/simulations

Method	Categories	Details	References
Data retrieval from databases	Energy consumption/saving	Background data for transport, electricity and fuel consumption	Rocchi *et al*. (2018)
		Energy production (provides PV electricity generation estimates and includes measured solar irradiation for European locations)	Luddeni *et al*. (2018)
	Cost data	Price of natural gas, electricity, cost data and growth rate of gas/labor/electricity/materials;	Pombo *et al*. (2016)
		Calculating capital costs of each retrofit	Afshari *et al*. (2014)
	External condition	Meteorological data (e.g. Annual profiles of hourly outdoor temperature, solar radiation, wind speed and relative humidity for the studied location)	Dodoo *et al*. (2017); Ferrari and Beccali (2017); Teres-Zubiaga *et al*. (2015)
		Weather data (e.g. external temperature, solar radiation)	Silvero *et al*. (2019); Valdiserri and Biserni (2016)
	Information related to construction and equipment	Building operation information and properties (e.g. ventilation rate, the internal heat gains of person occupancy, equipment load and lighting load setting, hourly schedules over the year of occupancy, DHW need, lighting and electrical equipment power densities)	Ascione *et al*. (2017); Hong *et al*., (2015); Paiho *et al*. (2015); Song *et al*. (2017)
		Building information (e.g. footprint, use and floor number)	Afshari *et al*. (2014)
		Inventory data (e.g. the materials, fore-ground data related to the main production and assembly processes; information about the raw material usage, extraction, production and transportation of construction material and all associated environmental impacts, such as emissions to air and water, global warming potential (GWP) data)	McGrath *et al*. (2013); Pombo *et al*. (2016); Rocchi *et al*. (2018); Shao *et al*. (2014); Techato *et al*., (2009)

		Inventory analysis (the importance ratios of environmental and economic performances are defined equally as 50% from database)	Cetiner and Edis (2014)

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Method	Categories	Details	References
Data retrieval from databases	Information related to construction and equipment	Other data (e.g. Leaf Area Index (the ratio of total leaf area to the cultivated floor area); data for specific emissions due to the use and the life cycle of one unit of energy)	Cellura *et al*. (2013); Ward and Choudhary (2014)
		List of alternative energy efficiency measures (EEMs) from software	Shao *et al*. (2014); Wang *et al*. (2015)
		Energy consumption habits	Tadeu *et al*. (2018)
From simulation	Energy consumption	Energy consumption	Copiello *et al*. (2017)
	Cost data	Energy prices and price changes rate (from historical and dynamics of energy price changes simulation)	Kumbaroglu and Madlener (2012)
	External condition	Climate data (from software)	Liu *et al*. (2015)
		Solar gain	Valdiserri and Biserni (2016)
		Generation of the exterior climate (from the CIBSE test reference year file)	Hall *et al*. (2013)

- For the unspecified data collection methods, they were presented in Table 2.25.

Table 2.25. Unspecified method

Method	Categories	Details	References
Unspecified	Energy consumption	Energy consumption	Hong *et al*. (2015); Peng *et al*. (2014)
	Cost data	Energy cost and reduction	Bleyl *et al*. (2019)
		Market information (not specified): price of standard coal, natural gas and electricity	Liu *et al*., 2018
	External condition	Weather/ Meteorological data	Aghamolaei (2019) Peng *et al*. (2014); Tokede *et al*. (2018); Xing *et al*. (2015)

	Information related to construction and equipment	Load profile	Asaee *et al*. (2017)
	Not mentioned	Not mentioned	Afshari *et al*. (2014); Wang *et al*. (2014)

2.8 Definition of retrofit indicators after consolidation

From the literature review process, 62 indicators were identified as applicable for measuring the performance of retrofit work. As some of these indicators bear the same meaning, they were consolidated, and the number of resultant indicators amounted to 52. Grouped into four aspects, there are 16 economic indicators (Table 2.26), 16 environmental indicators (Table 2.27), eight health and safety indicators (Table 2.28), and 12 users' perspective indicators (Table 2.29).

Table 2.26 Economic aspect (extracted from Ho et al., 2021)

Indicator	Meaning (References)
E1. Payback Period (year)	Time required to recover the project investment by project profits. (Albatici *et al*., 2016, Asaee *et al*., 2017, Ciulla *et al*., 2016, Dall'O *et al*., 2012, de Santoli *et al*., 2014, Ferrari and Beccali, 2017, Gugul *et al*., 2018, Heo *et al*., 2012, Hong *et al*., 2015, Jankovic, 2019, Krarti, 2015, Lee *et al*., 2015b, Liu *et al*., 2018, Menicou *et al*., 2015, Oree *et al*., 2016, Song *et al*., 2017, Teres-Zubiaga *et al*., 2015, Valdiserri and Biserni, 2016, Wang *et al*., 2014, Ward and Choudhary, 2014, Xu *et al*., 2016, Zhao *et al*., 2009a)
E2. Return on Investment (%)	Ratio between net profit and cost of the retrofit project. (Jankovic, 2019, Zheng and Lai, 2018)
E3. Internal rate of return (%)	Interest rate at which the net present value of all the cash flows from the retrofit project equal zero. (Bleyl *et al*., 2019, Liu *et al*., 2018, Tokede *et al*., 2018)
E4. Net present value ($)	Difference between the present value of cash inflows and the present value of cash outflows over a period of time. (e.g. an investment should be undertaken only when it is > 0. The best solution comes to the highest NPV scenario in a fixed lifespan.) (Afshari *et al*., 2014, Bleyl *et al*., 2019, Cetiner and Edis, 2014, Gugul *et al*., 2018, Kumbaroglu and Madlener, 2012, Leal *et al*., 2015, Song *et al*., 2017, Teres-Zubiaga *et al*., 2015, Tokede *et al*., 2018, Valdiserri and Biserni, 2016, Wang *et al*., 2014, Wang and Holmberg, 2015)
E5. Weighted Average Cost of Capital (%)	The weighting and cost of debt and equity. It reflects perceived risks and barriers of investment. (Bleyl *et al*., 2019)
E6. Peak demand savings ($)	Association with avoiding the construction of new power plants. (Krarti, 2015)
E7. Mean cost of intervention saved ($/kWh)	The average amount of money saved from intervention per kWh. (e.g. for wall: 0.07€/kWh saved, windows: 0.14€/kWh saved) (de Santoli *et al*., 2014, Zhao *et al*., 2009a)
E8. Annual energy cost savings($/year)	The among of energy cost being saved per year from the implementation of retrofit project. (Albatici *et al*., 2016, Asaee *et al*., 2017, Bleyl *et al*., 2019, Ciulla *et al*., 2016, Dall'O *et al*., 2012, De Tommasi *et al*., 2018, Krarti, 2015, Rodrigues and Freire, 2017, Tokede *et al*., 2018, Xing *et al*., 2015)
E9. Profit ($)	Revenue (e.g. selling the generated electricity to the grid.) (Leal *et al*., 2015, Song *et al*., 2017, Wang *et al*., 2014)

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Indicator	Meaning (References)
E10. Net Cash Flow ($/year)	Cash in-flow and out-flow for the building retrofit measures. (e.g. cost of annual energy consumption based on building improvement minus the cost of annual energy consumption based on retrofit) (Bleyl *et al.*, 2019, Gugul *et al.*, 2018)
E11. Investment cost ($)	Total amount of money spent for the retrofit project. (Dall'O *et al.*, 2012, de Santoli *et al.*, 2014, Kumbaroglu and Madlener, 2012, Leal *et al.*, 2015, Shao *et al.*, 2014, Song *et al.*, 2017, Wang *et al.*, 2014, Xing *et al.*, 2015)
E12. Normalized investment cost ($/m^2)	Total amount of money spent for the retrofit project per square meter. (Antipova *et al.*, 2014, Bleyl *et al.*, 2019, Kumbaroglu and Madlener, 2012, Luddeni *et al.*, 2018, Tadeu *et al.*, 2018)
E13. Retrofit and operational costs ($)	Total amount of money spent for retrofitting and operation. (e.g. sum of money spent in building replacements, equipment replacements, equipment operation and maintenance (O&M) and the bill of the energy.) (Antipova *et al.*, 2014, Fernandes *et al.*, 2018, Leal *et al.*, 2015)
E14. Global Cost ($/m^2)	Total amount of money spent for retrofit and operation per meter square. (e.g. total amount of money spent per meter square, including initial investment costs, replacement costs of the retrofit measures, the discounted public financial incentives and lifecycle operating costs.) (Ascione *et al.*, 2017, Krarti, 2015, Song *et al.*, 2017)
E15. Life Cycle Cost ($)	Sum of all recurring and one-time costs of the retrofit project over the full life span. (Bleyl *et al.*, 2019, Cetiner and Metin, 2017, Copiello *et al.*, 2017, Luddeni *et al.*, 2018, Pombo *et al.*, 2016, Ruparathna *et al.*, 2017, Wang and Holmberg, 2015)
E16. Revocability Cost ($)	The propensity that future costs can vary over time in a building across its estimated life. (e.g. 'energy costs reduction due to installation of passive systems, renewable systems or energy-efficient gadgets', 'security cost reduction due to automation of building entry and exit controls', and 'maintenance cost reduction due to improved data retention and management using systems such as Building Information Modelling.) (Tokede *et al.*, 2018)

Table 2.27 Environmental aspect (extracted from Ho et al., 2021)

Indicators	Meaning (References)
En1. CO_2 emission payback periods	Period over which the retrofitted system reduces CO_2 emission to recover CO_2 that produce initially. (Huang *et al.*, 2012)
En2. Global warming potential (kg $CO_{2\text{-eq}}$)	A measure of how much heat a greenhouse gas traps in the atmosphere during retrofitting, relative to carbon dioxide. (Shao *et al.*, 2014)
En3. Emission class indices	Classification of the greenhouse gases emission performance ($kgCO_2/m^{2}$-year) into Grade A to G. (Gugul *et al.*, 2018)
En4. Energy generation (%)	The energy generated by the retrofit measures (e.g. by using photovoltaic panels). (Aghamolaei, 2019)
En5. Energy payback period (year)	Period over which the retrofitted system produces energy to recover the energy used to produce the system initially. (Huang *et al.*, 2012)
En6. Reduction of electrical peak demand (%)	Percentage of reduction of peak demand in electricity. (Afshari *et al.*, 2014)
En7. Reduction of peak cooling load (%)	Percentage of reduction of peak demand in cooling load. (Luddeni *et al.*, 2018)
En8. Energy consumption class	Classification of energy performance (kWh/m^{2}-year) of houses from energy class A to G from the benchmarking. (Gugul *et al.*, 2018)
En9. Total site energy (GJ) [energy consumption]	Total operational energy consumption and or per a specific period (e.g. kWh/year) (Afshari *et al.*, 2014, Cellura *et al.*, 2013, De Tommasi *et al.*, 2018, Gugul *et al.*, 2018, Huang *et al.*, 2012, , Paiho *et al.*, 2015, Peng *et al.*, 2014, Shao *et al.*, 2014, Zhao *et al.*, 2009b)
En10. Life Cycle Analysis	Assessment of the life cycle environmental impact in the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. (Antipova *et al.*, 2014, Cetiner and Edis, 2014, Huang *et al.*, 2012, McGrath *et al.*, 2013, Pombo *et al.*, 2016, Rocchi *et al.*, 2018, Tadeu *et al.*, 2015)

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Consolidated Indicators	Meaning	Original Indicator (References)
En11. Δ Carbon emission (%)	Difference in carbon emission before and after retrofit and expressed in different unit.	Reduction in carbon emission (%) (Asaee *et al*., 2017, Bleyl *et al*., 2019, de Santoli *et al*., 2014, Jankovic, 2019, Luddeni *et al*., 2018, Touchie and Pressnail, 2014, Ward and Choudhary, 2014)
		Reduction in carbon emissions (Tonnes per year) (Bao *et al*., 2012, Touchie and Pressnail, 2014, Ward and Choudhary, 2014)
En12. Δ Carbon emission ($kgCO_{2\text{-}eq}/m^2year$)		Reduction in greenhouse gases (Mt of CO2e) (Asaee *et al*., 2017)
		Carbon emission, with different unit (e.g. g, tonnes, $kgCO_2$/year, kg CO_2/m^2-year) (Ferrari and Beccali, 2017, Gugul *et al*., 2018, Henriques *et al*., 2015, Huang *et al*., 2012, Zheng and Lai, 2018)
		Greenhouse gas emissions, with different units ($kgCO_2eq/m^2$, $kgCO_{2\text{-}eq}/m^2year$) (Ferrari and Beccali, 2017, Wang *et al*., 2015)
En13. Energy savings (%)	Amount of energy saved as a result of the retrofit project.	Energy saving (%) (Aghamolaei, 2019, Asaee *et al*., 2017, De Tommasi *et al*., 2018, Dodoo *et al*., 2017, Liu *et al*., 2018, Luddeni *et al*., 2018, Menicou *et al*., 2015, Peng *et al*., 2014, Teres-Zubiaga *et al*., 2015, Wang *et al*., 2014, Wang and Holmberg, 2015, Ward and Choudhary, 2014, Zhao *et al*., 2009b)
		Energy saving (e.g. kWh, Tonnes, W, PJ) (Asaee *et al*., 2017, Bao *et al*., 2012, Henriques *et al*., 2015, Hong *et al*., 2015, Huang *et al*., 2012, Touchie and Pressnail, 2014)
En14. Normalized energy savings (kWh/m^2year)		Energy savings per meter square (kWh/m^2) (Teres-Zubiaga *et al*., 2015)
		Annual energy savings per meter square (kWh/m^2 year) (Pombo *et al*., 2016, Wang and Holmberg, 2015, Wang *et al*., 2015, Xu *et al*., 2016)
		Annual energy savings (e.g. GWh/year, kWh/year) (Dall'O *et al*., 2012, Hall *et al*., 2013, Krarti, 2015, Song *et al*., 2017)

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Consolidated Indicators	Meaning	Original Indicator (References)
En15. Δ Electricity consumption per year (kWh/year)	Saving in electricity consumption per year as a result of the retrofit project.	Annual electricity consumption (kWh/year)/ Annual energy consumption (kWh/year) (As electricity contributes more than 90% of the energy in commercial sectors, it used electricity as an easy measuring indicator.) (Afshari *et al*., 2014, Ascione *et al*., 2017, Fernandes *et al*., 2018, Gugul *et al*., 2018, Leal *et al*., 2015, Liu *et al*., 2015, Liu *et al*., 2018, Pombo *et al*., 2016, Shao *et al*., 2014, Teres-Zubiaga *et al*., 2015)
En16. Δ Normalized energy consumption (kWh/m^2year; kWh/m^2month)	Difference in energy consumption per meter square of the buildings after undertaking retrofit during a specific time period.	Normalized energy consumption (e.g. kWh/m^2year; kWh/m^2month) (de Santoli *et al*., 2014, Deb and Lee, 2018, Gourlis and Kovacic, 2016, Gugul *et al*., 2018, Leal *et al*., 2015, McGrath *et al*., 2013, Tadeu *et al*., 2015, Touchie and Pressnail, 2014, Valdiserri and Biserni, 2016, Wang and Holmberg, 2015, Wang *et al*., 2015, Zhao *et al*., 2009b)

Table 2.28 Health and safety aspect (extracted from Ho et al., 2021)

Additionally, papers apart from the 67 papers that are relevant to this aspect were also included.

Consolidated Indicators	Meaning (References)
HS1. Target % in removal of statutory orders (Renamed in focus group: HS1* Ratio of actual to target number of statutory orders removed (%))	Fulfillment of the target level in removal of statutory orders over a certain period. (Buildings Department, 2002, Lai and Man, 2018a).
HS2. Target % in reduction of number of accidents per year (Renamed in focus group: HS2* Ratio of actual to target number of accidents per year reduced (%))	Fulfillment of the target level in reduction of number of accidents over a certain period. (Lai and Man, 2018a)

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Consolidated Indicators	Meaning (References)
HS3 Target % in reduction of number of legal cases per year (Renamed in focus group: HS3* Ratio of actual to target number of legal cases per year reduced (%))	Fulfillment of the target level in reduction in number of legal cases due to underperformance of facilities per year. (Lai and Man, 2018a)
HS4 Target % in reduction in number of compensation cases per year (Renamed in focus group: HS4* Ratio of actual to target number of compensation cases per year reduced (%))	Fulfillment of the target level in reduction in number of cases (due to underperformance of facilities) where the injured parties are compensated per year. (Lai and Man, 2018a)
HS5 Target % in reduction in amount of compensation paid per year (Renamed in focus group: HS5* Ratio of actual to target reduction in amount of compensation paid per year reduced (%))	Fulfillment of the target level in reduction in number the amount of compensation paid to the injured parties (due to underperformance of facilities) per year. (Lai and Man, 2018a)
HS6 Target % in reduction in number of health and safety complaints per year (Renamed in focus group: HS6* Ratio of actual to target number of health and safety complaints per year reduced (%))	Fulfillment of the target level in reduction in number the health and safety complaints (due to underperformance of facilities) per year. (Lai and Man, 2018a)
HS7 Target % in reduction in number of lost workdays per year (Renamed in focus group: HS7* Ratio of actual to target number of lost workdays per year reduced (%))	Fulfillment of the target level in reduction in number of days off (due to work-related illness/injuries arising from underperformance of facilities) per year. (Lai and Man, 2018a)

(Cont')

Consolidated Indicators	Meaning (References)
HS8 Target % in reduction in number of incidents of specific disease per year (Renamed in focus group: HS8* Ratio of actual to target number of incidents of specific disease per year reduced (%))	Fulfillment of the target level in reduction in number incidents of specific disease (with medical certificate) per year. (Lai and Man, 2018a)

Table 2.29. Users' perspective (extracted from Ho et al., 2021)

Consolidated Indicators	Meaning/ Relevant Standard	Original Indicator (References)
U1. Δ Predicted Mean Vote index (PMV)	Prediction in comfort response of people through a seven-point thermal sensation scale with a range of +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly neutral), -2 (cool) and -3 (cold) by comparing its performance before and after retrofit.	Predicted Mean Vote index (PMV) (Liu *et al.*, 2015, Silva *et al.*, 2013b, Zuhaib *et al.*, 2018)
U2. Δ Predicted Percentage of Dissatisfied (PPD) (%)	Prediction the percentage of people who feel more than slightly warm or cool (it has an empirical relationship of PMV with the PPD) and compare its performance before and after retrofit.	Predicted Percentage of Dissatisfied (PPD) (%) (Liu *et al.*, 2015, Silva *et al.*, 2013b, Zuhaib *et al.*, 2018)
U3. Δ Indoor air temperature (ºC)	Fulfillment of the target indoor air temperature. (For example: frequency of occurrence internal air temperatures less than or equal to 21 °C before and after retrofit.)	Indoor air temperature (ºC) (Bao *et al.*, 2012, Gourlis and Kovacic, 2016, Jankovic, 2019, Zuhaib *et al.*, 2018)
U4. Δ Discomfort hours in summer (%)	Fulfillment of the target comfort hours in summer. (For example: The percentage of hours when operative temperature is > 27 ◦C by the EN 15251 for buildings in the Category II, corresponds to the overheating rate.)	Discomfort hours in summer (%) (Ascione *et al.*, 2017, Fernandes *et al.*, 2018, Liu *et al.*, 2015, Silvero *et al.*, 2019)
U5. Thermal comfort level	Classification of indoor environment into different classes (Best/ Good/ Acceptable/ Unacceptable) with respect to their PPD and PMV.	(Liu *et al.*, 2015)

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Consolidated Indicators	Meaning/ Relevant Standard	Original Indicator (References)
U6. Δ Ventilation and infiltration rates (h^{-1})	Comparison of the ventilation and infiltration performance before and after retrofit. (e.g. The standards for minimum rates of ventilation are specified in indoor quality standards such as ASHRAE Standard 62 and EN15251.)	Ventilation and infiltration rates (h^{-1}) (Liu *et al.*, 2015, Peng *et al.*, 2014, Silva *et al.*, 2013b, Zuhaib *et al.*, 2018)
U7. Δ Indoor CO_2 levels (ppm)/other harmful substances	Reduction in concentration of carbon dioxide or harmful substances as a result of the retrofit project.	Indoor CO_2 levels (ppm)/other harmful substances (Liu *et al.*, 2015, Silva *et al.*, 2013b, Zuhaib *et al.*, 2018)
U8. Internal air quality (Renamed in focus group: U8* Target IAQ class)	IAQ is generally expressed in terms of CO_2 concentration and ventilation required for reducing the concentration of indoor air pollutants. The mould growth potential (mm), indoor RH fluctuation (%), and improved percentage of complaints in air quality can also be compared before and after retrofit.	(Bao *et al.*, 2012, Hall *et al.*, 2013, Jankovic, 2019, Liu *et al.*, 2015)
	Target (Good/Excellent) Class of the Environmental Protection Department's IAQ Certification Scheme obtained as a result of the retrofit project.	(Environmental Protection Department, 2017)
U9. Δ Work productivity	Improvement in the amount of output produced per work hour due to retrofit. (e.g. it can be reflected by (1) active days gained from reducing sick days and (2) healthy life year loss.)	Work productivity (Bleyl *et al.*, 2019, Liu *et al.*, 2015)
U10. Δ Workforce performance (€/m^2)	Measures of improvement in how well an individual performs a job, role, task or responsibility. (e.g. The subjective comfort experience of building users, where the survey polls on 6 aspects of comfort (thermal comfort, air quality, acoustics, lighting, individual control and office environment and cleanliness) on the work performance impact.)	Workforce performance (€/m^2) (Bleyl *et al.*, 2019)

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Consolidated Indicators	Meaning/ Relevant Standard	Original Indicator (References)
U11. Visual comfort –Δ workplane illuminance (lux) (Renamed in focus group: U11* Target Work plane illuminance (lux))	The target workplane illuminance obtained as a result of the retrofit project.(e.g. recommended minimum workplace illuminance given in EN15251 for typical occupancy zones.)	Work plane illuminance (lux) (Silva *et al*., 2013b, Zuhaib *et al*., 2018)
U12. Acoustic comfort –Δ nosie level (Leq - equivalent continuous weighted sound pressure level (dBA)) (Renamed in focus group: U12* Target Equivalent continuous weighted sound pressure level (dBA))	The target Equivalent continuous weighted sound pressure level (dBA) obtained as a result of the retrofit project.	Equivalent continuous weighted sound pressure level (dBA)) (Bao *et al*., 2012, Liu *et al*., 2015, Zuhaib *et al*., 2018)

2.9 Summary

Timely and appropriate implementation of retrofit projects is crucial to the performance of buildings and hence the sustainability of the built environment. In literature review, evaluation methods for building retrofit were reviewed thoroughly and systematically, with the supplement review of papers concerning other issues for a clearer picture of the whole building retrofit process. It includes the retrofit measures adopted, applied building types, investigation focus, data collection methods, different types of simulation models and real application examples were reviewed. A large number of indicators, as the literature review showed, are applicable for measuring the performance of building retrofits. After consolidation and refinement, a total of 52 indictors were compiled, which comprise 16 economic indicators, 16 environmental indicators, 12 users' perspective indicators and eight indicators in the health and safety aspect.

Although these KPIs are useful in theory, much time and effort are needed for evaluation and applied the KPIs in real practice. These indicators identified for retrofitting of commercial buildings can be further examined by conducting focus group meeting, surveys, and interviews to sort out and testify the appropriateness of the shortlisted indicators. The important and feasible assessing criteria in assessing building retrofit performance will be investigated and analyzed for method development and validate the protocol in a later stage.

Chapter 3 Methodology

3.1 Introduction

As mentioned before, there is limited holistic performance evaluation method for building retrofit. To develop such a method for commercial buildings, this research was conducted and consisted of four stages, namely literature review, carrying out focus group study, surveys, and interviews. Through undertaking a serios of rigorous studies, useful data and opinions can be collected for method development and validation. This chapter describes the process, research methods adopted and rationales of their application in this research.

3.2 Research process

Methodology refers to “the overarching strategy and rationale of your research project. It involves studying the methods used in your field and the theories or principles behind them to develop an approach that matches your objectives”. For methods, they are “the specific tools and procedures used to collect and analyze data (for example, experiments, surveys, and statistical tests)” (Shona, 2019).

For quantitative methods, the analysis was based on numbers, and the methods include how to prepare the data before analyzing it such removing outliers and transforming variables by software (e.g. SPSS, Stata or R) and performed by statistical test (e.g. t-test, simple linear regression.) For qualitative methods, the analysis was based on language, images, and observations, such as content analysis, thematic analysis and discourse analysis (Faryadi, 2019). A hybrid of qualitative and quantitative methods was adopted in this study for data collection as follows:

Table 3.1 Summary of methods applied during this study

Stage of study	Details	Type of method
1	Literature review	(Identification of research gaps)
2,4	Focus group, in-depth interviews	Qualitative
3	Online survey	Quantitative

Table 3.2 Methodology applied in the research process

Objectives	Type of Data required	Data collection Approach	Analysis
To identify indicators applicable to measuring the performance of retrofit projects for commercial buildings.	Performance evaluation methods for building retrofit. Economic, environmental, health and safety, users' perspective indicators	Literature Review	PRISMA method
To shortlist the identified indicators to become key performance indicators (KPIs) for use in assessing building retrofit performance.	Economic, environmental, health and safety, users' perspective indicators	Focus group study (Qualitative) Industry-wide survey (Quantitative)	Mean score, U-test, H-test, Content analysis
To determine importance weights of each of the KPIs.	Examine the relationships between the shortlisted KPIs Pair-wise comparisons matrices between caterogies and individual KPIs	Interview with experts (Qualitative)	ANP
To develop a credible assessment method based on the KPIs, for evaluating building retrofit performance for commercial buildings.	Relative importance weights of each of the KPIs		Mean, median, modes, ranks
To validate the applicability of the developed assessment method.	Actual data before and after retrofit projects	Questionnaire Pilot case study	Content analysis

Stage 1: Literature review

Literature review was conducted to identify the methods and indicators available for assessing building retrofit performance. It is essential for research planning and development, with further effort made upon the commencement of this proposed study to search and review any new literature.

Stage 2: Focus group meeting

In order to identify the most appropriate indicators in assessing building retrofit among different aspects, a focus group approach could allow participants to explore and examine each other's point of view (Ritchie and Lewis, 2003). Their opinions regarding retrofit performance assessment will be collected. It is not suitable to use surveys as they usually have a low return rate and they will only collect board-brush information and cannot assist further exploration of issues (Minichiello and Kottler, 2010). For the focus group meeting, hypothesis developed through the discussion may be used for investigation at a later stage of the study (Chapman *et al*., 2005). Therefore, a focus group meeting was convened to probe into the underlying assumption and answers of respondents at necessary depth and collect the richest possible information (Minichiello and Kottler, 2010). Data collected from the meeting was of high quality because the respondents are under the pressure of further elaborating their opinions or challenged by other group members (Merton, 1987, Wilkinson, 1998). The data are also more representative because of "their languages and concepts, their frameworks for understanding the world" (Wilkinson, 1998). Previous focus group interviews include identifying the key adaptive management strategies used in a lighting retrofit process (Kim *et al*., 2017), discussing the critical barriers and appropriate strategies for the application of building information modeling

(Salleh and Fung, 2014), reviewing the causes of quality failures in building energy renovation projects (Qi *et al*., 2020).

The optimal size of focus group is typically between 6 to 12 members (Fern, 2001, Kamberelis and Dimitriadis, 2005, Stewart *et al*., 2007). It is to ensure maximum interaction and input provided from them. Some participants may be concerned about the privacy issue and possibility of over-disclose the sensitive personal information (Dennis *et al*., 2013). Hence, many researchers developed strategies, for example, provide a clear understanding of the nature of focus group meeting, guideline at the beginning of meeting, individuals and group debriefing at its conclusion (Smit and Cilliers, 2006, Smith, 1995). It should also provide special care to all group members and reinforce their sense of responsibility for keeping those shared information during conversation confidential (Smit and Cilliers, 2006). The primary means of focus discussion on target topic is to develop a protocol (Dennis *et al*., 2013). "Topic guide" that outlines the issues covered, or a "questioning route" that provides with a list of more detailed questions, are examples that can facilitate the discussion (Krueger, 2009). The focus group meeting, was held with experienced FM professionals, is useful to find out if the developed protocol covers the essential indicators and thus fit for use in the next stages. The details of focus group will be discussed in the next chapter.

<u>Stage 3: Survey</u>

There are different types of sampling methods as shown below (Faryadi, 2019):

- Random sampling (every member of the population has a chance of being part of the study)

- Non-random sample (the population is either unknown or too large to be sampled individually)

For taking the desired samples, other sampling such as (Faryadi, 2019):

- Quota sampling (study a specific characteristic of the target population), accidental sampling (similar to quota sampling, but without a selected predetermined characteristic that is obvious or visible),
- Purpose sampling (based on personal preference and judgment from the researchers), expert sampling (select only the experts that you know they are knowledgeable and will give you the information you require),
- Snow-ball sampling (first select a few individuals of the target population, after providing the necessary information, ask them to suggest suitable people to conduct the participate in a similar interview or survey),
- Mixed sample (mixture or random and non-random sampling)

An online survey was conducted, and it is a simple means to get access to a large group of potential respondents, distributed at very low costs and can be launched very quickly (Bethlehem, 2009). Five suggestions were drawn from the study of Kirchherr & Charles (2018) for the enhancement of sample diversity of snowball samples:

1. Prior personal contacts are not essential for achieving sample diversity but helpful to generate new contacts during research which can be labor-intensive.
2. Sample seed diversity is important for sample diversity.
3. Face-to-face interviews build trust and thus help to generate further referrals.
4. Persistence (within reason) is helpful in securing interviews.

5. Sample diversity is not necessarily enhanced if a seed is advanced over numerous waves. While more waves can lead to novel insights, the number of waves pursued is not a definitive indicator for sample diversity. Even very few waves can yield access to particularly difficult-to-access populations.

As such, a mixed ways of snowball sampling method and connections obtained from FM organization, Building Services Operation and Maintenance Executives Society (BSOMES) were applied in data collection for online survey. The response from the FM practitioners was collected to rate the importance of the key performance indicators (KPI). The relative importance of the indicators was evaluated by using five-point Likert scale (1-5) and shortlist the KPIs. If evaluate all the identified indicators in literature reviews, it requires much effort and laboring cost/workload to record and process all the needed data for evaluation. In order to evaluate the retrofit performance efficiently, the non-essential indicators can be removed through an industry-wide survey and consolidate their opinions. The details of focus group will be discussed in the chapter 5.

Stage 4: Interviews

As interviews can increase the validity of study findings and cross-check the reliability of the study results in previous stage (Phizacklea, 1995). In-depth interviews were conducted with FM professionals who look after different type of commercial buildings with different scale (e.g. small and large building) and age (e.g. new and old building). A short brief and explanation of the project were given to the participants at the beginning of the interview to ensure there was a clear understanding and interpretation of the topics.

During the interview, qualitative approach was also adopted, whereas the key for qualitative analysis is not just to deconstruct the interview or discussion data into bits and pieces (e.g. codes), but “rather to define the research question from participants’ perspectives, derive underlying themes that connect these perspectives and give weight to the researcher’s interpretations and implications associated with the research question under investigation”. The benefit of this approach is that instead of focusing too much on coding, the complete absorption and understanding of each interview allow researcher to fully internalize each participant’s relationship to the research question by taking account into i) not all conversation has equal value (e.g. side conversation or inappropriate use of words that needs to be redefined); ii) contradicting themselves or change of mind; iii) tone or emotion expressed conveys meaning and is taken into account to aid the researcher’s understanding (Margaret and Roller, 2020).

Stage 4.1. Method development

After collecting the information in the interview, a comprehensive assessment method was developed by integrating various aspects (e.g. economic, environmental and users’ perspective). The assessment method made use of the importance weights of the KPIs and their corresponding overall weighted performance scores in various aspects. Through constructing the Analytic Network Process (ANP), the relationship between KPIs were unveiled. The proposed assessment method was pilot tested. Field data, to be collected from a pilot interview with an FM professional working on a typical commercial building, was used to test the usability of the assessment method. The applicability of the KPIs was validated, because some relevant data may be insufficient (e.g. improper in measurements and keeping records), confidential (e.g. financial information in companies) and unknown by the roles of the FM professionals (e.g. some financial data concerning profits and revenue). Improvements was made to the assessment method until the test result is found to be comprehensive and satisfactory. The details of ANP will be shown in chapter 6.

<u>Stage 4.2: Method validation</u>

Data collected from the interviews were processed to evaluate and validate the building retrofit performance of the commercial buildings by using the developed analytic method. Follow-up actions may be required to find out and organize the data to collect sufficient data for evaluation. Any observations and opinions collected in this stage, which were qualitative in nature, were also be collected. The applicable of the finalized key performance indicators were tested to see whether the established assessment method can meet their needs in evaluating building retrofit performance. The feasibility and the encountered difficulties or weakness of the established evaluation method were fully unveiled. The details of case studies will be shown in chapter 7.

3.3 Analytic Hierarchic Process and Analytic Network Process

3.3.1. Analytic Hierarchic Process (AHP)

The Analytic Hierarchic Process (AHP) is a decision-making methods developed by Saaty (1980). It evaluates the problems through several levels of hierarchy and the decision element is independent. The top layer of the hierarchy is the main goal of the decision problem, and the lower levels are the factors with respective to the upper level, and this AHP approach allows comparison of the relative importance of individual factors. The AHP is useful for making multicriteria decisions related to benefits, opportunities, costs and risks (Saaty, 2014a). For the AHP method, it can be summarized into the following seven pillars (Vaidya and Kumar, 2006):

1. State that problem.
2. Broaden the objectives, actors and outcome of problems.
3. State out the criteria that affect the behavior.
4. Decompose the problem in a hierarchy of various levels of goal, criteria, sub-criteria and alternatives. A typical hierarchy model is shown in Figure 3.1.

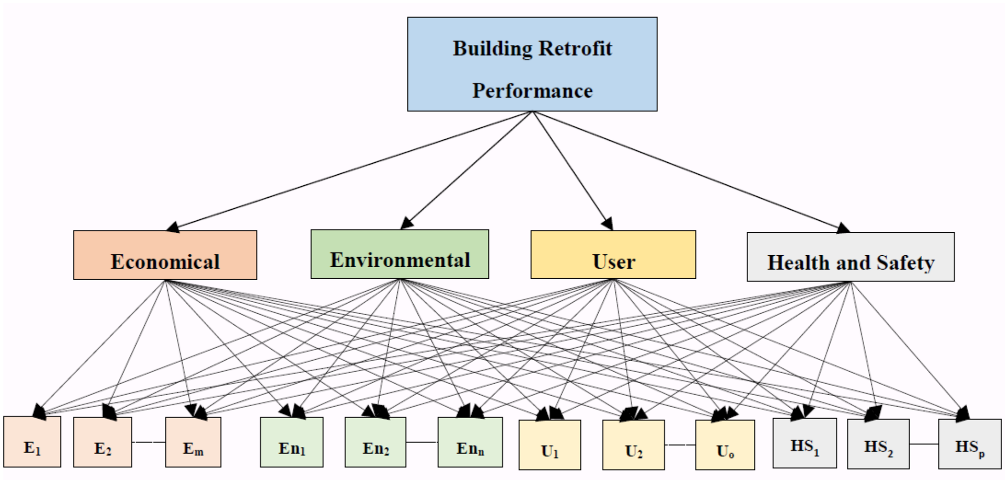


Figure 3.1 A three level hierarchy

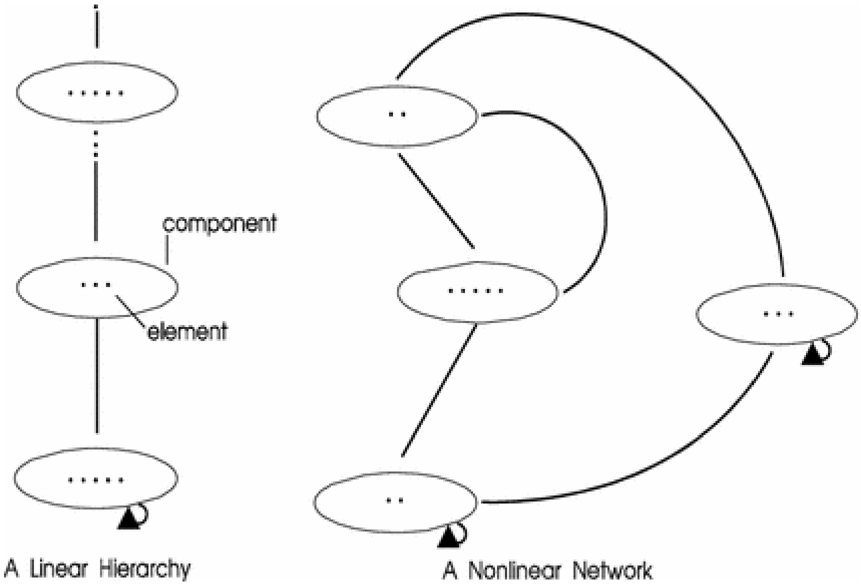


Fig. 1.2

Figure 3.2 Structural difference between a linear and a nonlinear network
(Extracted from Saaty, 2012)

5. Compare each element in that particular level and calibrate them on the numerical scale.
6. Calculate the maximum eigenvalue, consistency index CI, consistency ratio CR, and normalized values for the criteria or alternatives.
7. For the maximum Eigen value, CI and CR, if they are satisfied then decisions will be taken based on the normalized values. Otherwise, the procedure is repeated util it falls into a desired range.

3.3.2 Difference between networks and hierarchy

A hierarchy has a goal or cluster or a source node. It is a linear top-down structure with no feedback from the lower level to upper one. However, it has a loop at the lowest level to show that each alternative in that level is independent from each other. For network, it spreads out in all directions where the clusters of elements are not arranged in an order. Influence can be transmitted from a cluster to another one. It may have or may not have feedback to other clusters.

3.3.3 Analytic Network Process (ANP)

The ANP approach is generalized from the AHP (Saaty, 1996). It considers the problems with dependence and feedback and allows more complex inter-relationships among individual decision factors. It can be used to answer two kinds of questions: (i) Which of two elements is more dominant with respect to the criterion, (ii) Which of two elements influences the third element more with respect to the criterion (Saaty, 2004a). Figure 3.3 showed the theoretical framework for building retrofit performance assessment criteria. The performance of each dimension can be measured using its relevant indicators, which can be quantifiable for assessment. The indicators and other relevant data were identified through focus group meeting to establish the ANP structure. It is necessary to address the relationship between the parameters to allow decision makers to achieve better performance in building retrofit.

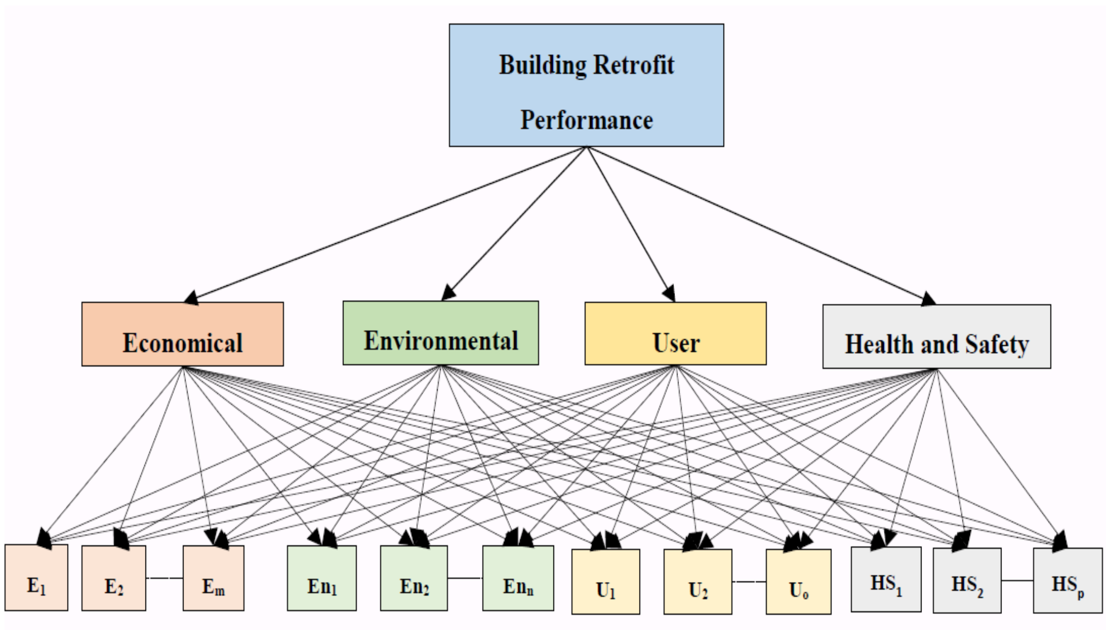


Figure 3.3 A theoretical hierarchy of evaluating building retrofit performance

Four main steps of ANP methods are as follows: 1) construction of model, 2) pairwise comparisons and local priority vectors, 3) supermatrix formation and 4) final priorities and selection (Saaty, 1996).

(i) Construction of model:

The shortlisted indicators identified in focus group can be reviewed by questionnaire surveys before model construction in software. Through using uni-direction and/or bi-direction arrows, the relationship between elements/nodes can be shown clearly.

(ii) Pairwise comparisons and local priority vectors:

After constructing the structure of problem, decision makers are asked to answer a series of pairwise comparison matrices. The relative importance of criteria can be found by different prioritization methods. Six popular methods for deriving priority vector include: eigenvector method, arithmetic mean method, least squares method, logarithmic least squares method, geometric mean method and fuzzy programming method (Ramík J., 2020).

Through comparing the elements pairwisely with respect to their importance on other elements by using a scale of 1-9 (Table 3.3) (*"1" = "Equal importance", "9= Absolute importance", "2, 4, 6, 8" = intermediate value*). The fundamental scale used for the judgments is shown in Table 3.4.

Table 3.3 Perceived relative importance between A and B

Perceived relative importance between Parameter A and Parameter B																		
Parameter A	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Parameter B

Table 3.4 Fundamental scale for the judgments
(Extracted from Saaty and Sodenkamp, 2010)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
1.1-1.9	When activities are very close a decimal is added to 1 to show their difference as appropriate	Perhaps a better way than assigning the small decimals is to compare two close activities with other widely contrasting ones, favoring the larger one a little over the smaller one when using the 1–9 values.
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A logical assumption

For inverse comparison, a reciprocal value is used and that is $s_{ij} = 1/s_{ij}$, and s_{ij} is the importance of i^{th} element as compared with the j^{th} element. The local priority vectors can be obtained by the eigenvector method for each pairwise comparison matrix (For the eigenvector w with the maximum eigenvalue of the pairwise, comparison matrix is the final expression of preferences between the elements).

To test the consistency of a pairwise comparison, a consistency ratio (CR) can be known by using the ratio of consistency index (CI) [where C.I.= (λmax – n)/(n-1) ≡ μ], and random index (RI), [where it formed from the average of the reciprocals' eigenvalues]. It can be expressed in equation (3.1) (Saaty and Sodenkamp, 2010). CR<0.1 is considered as acceptable (Xu *et al*., 2015).

$$CR = C.I./R.I. = \mu/R.I. \qquad \text{(eq.3.1)}$$

(iii) Supermatrix formation:

The local priority vectors were entered into the appropriate columns of a supermatrix. It represented the influence priority of an element on the left of the matrix acts on an element at the top of matrix. A standard form of supermatrix be illustrated as follows (eq.3.2):

$$W = \begin{array}{cc} & \begin{array}{cccc} P_1 & P_2 & \cdots & P_N \\ p_{11}\cdots p_{1n_1} & p_{21}\cdots p_{2n_2} & \cdots & p_{N1}\cdots p_{Nn_N} \end{array} \\ \begin{array}{cc} P_1 & \begin{array}{c} p_{11} \\ \vdots \\ p_{1n_1} \end{array} \\ P_2 & \begin{array}{c} p_{21} \\ \vdots \\ p_{2n_2} \end{array} \\ \vdots & \vdots \\ P_N & \begin{array}{c} p_{N1} \\ \vdots \\ p_{Nn_N} \end{array} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix} \end{array}$$

where P_i is the cluster decomposed in the model; pin are elements involved in P_i. The variable W_{ij} is the local priority vector from pairwise comparison, showing the importance of elements in P_i with respect to elements P_j. Zero were obtained in the matrix if there is no interdependency between elements.

(iv) Final priorities and selection:

After obtaining the unweighted supermatrix, the weighted supermatix and limit supermatrix can be found. To attain a convergence on importance weights, the weighted supermatrix was raised to limiting powers to obtain global priorities (eq.3.3). If there are two or more limiting supermatrices, the final priorities can be found by equation 3.4 (Tzeng and Huang, 2012):

$$\lim_{k \to \infty} W^k \qquad \text{(eq.3.3)}$$

$$\lim_{k \to \infty} \left(\frac{1}{N}\right) \sum_{j=0}^{N} W_j^k \qquad \text{(eq.3.4)}$$

where Wj is the jth limiting priority, N denotes the number of limiting supermatrices.

3.3.4 Advantages and disadvantages of using ANP

As decision making requires judgements, preferences, risk taking and feelings, this rational thinking may use logic based on clear assumptions to derive a conclusion. In the ANP measurement, it relies on the judgement of people. To understand the subjective understanding of people viewing “objective” in the real world, it is important to present the theories and validate them (Saaty, 2004b). ANP has advantages over AHP such as allow interdependency and complex relationships, non-linear network structure, real world representation of the situation by using clusters and consider tangible and intangible criteria in decision making (Saaty, 1999). However, there are still some disadvantages of using ANP, such as require extensive brainstorming for identifying attributes, a time intensive process for data collection, requires more calculation as compared to the AHP process, and omitted the subjectivity of the comparison (Agarwal and Shankar, 2003).

3.3.5 Applications of AHP and ANP

AHP methods were widely applied in various areas such as personal, social, manufacturing sector, political, engineering, education, industry, government, and others such as sports, management, etc. were presented. (Vaidya and Kumar, 2006). ANP studies can also be classified into nine application areas including (i) health, safety, and environmental management; (ii) hydrology and water management; (iii) business and financial management; (iv) human resources management; (v) tourism; (vi) logistics and supply chain management; (vii) design, engineering and manufacturing systems; (viii) energy management and (ix) other topics (Kheybari *et. al*, 2020).

In the construction industry, ANP has been widely applied for performance evaluation (Kheybari *et. al*, 2020) such as to evaluating the performance of adaptive façade systems in complex commercial buildings (Yitmen, *et al.*, 2021), select the most sustainable material for building enclosure (Mahmoudkelaye *et al.*, 2018). A weighting system for refurbishment building assessment scheme was developed in Malaysia by AHP (Xu *et al*., 2015).

A detailed review of applications of AHP and ANP were presented by Sipahi and Timor (2010) and observed that a significant number of studies were related to fuzzy AHP methodology although the accuracy of the fuzzy approach has been strongly criticized by authorities (Saaty, 2006). The AHP method was also used to evaluate the energy retrofit solutions for building types such as historical and residential buildings (Roberti *et al*., 2017, Silvero *et al*., 2019, Zhao *et al*., 2009a).

3.4 Scoring method

FM practitioners are building professionals that knowledge and work experience are gained through intensive interactions with the operations of the existing buildings they manage. Thus, their opinions on the change in the buildings' conditions are reliable. From Cetiner and Edis (2014), the overall sustainability performance of retrofit was determined by using the

equation (3.5):

$$SP_{i,j} = \frac{(NR_{i,j} \times m_n) + (CR_{i,j} \times m_c)}{100} \quad \text{(eq.3.5)}$$

where SP is the sustainability performance, NR is the environmental performance, CR is the economic performance, m is the importance ratio (%). The indices i and j are the building type and the retrofit alternative planned to use respectively. The sum of m_c and m_n is 100.

Similarly, the retrofit performance can be determined by considering combined effect of various aspects on a particular retrofit project, using the revised equation (3.6):

$$BRPI = \frac{\sum_{i=1}^{n} (E_i \times w_e + En_i \times w_{en} + U_i \times w_u + HS_i \times w_{ee})}{100} \quad \text{(eq.3.6)}$$

where BRPI is the building retrofit performance index, E is the identified economic indicator, En is the environmental indicator, U is the indicator of user comfort, HS is the indicator for health and safety, w is the weighting factor (%) corresponding the indicator number i. The sum of weighting is 100.

3.5 Summary

A credible assessment method was developed for evaluating building retrofit performance for commercial buildings by four stages: namely literature review, focus group, online surveys, and in-depth interviews. The AHP and ANP approach for evaluating indicators were also discussed with four major steps, including model construction, pairwise comparison and local priority vectors, supermatrix formation and final priorities. More details and results obtained from each stage of work will be explained in other chapters.

Chapter 4 Performance indicators for building retrofit: shortlisting through focus group study

4.1 Introduction

After identifying indicators from literature review, a focus group study was conducted to shortlist the most useful indicators. The procedures and discussion of the analyzed findings are reported in this chapter. The inclusion, newly added KPIs and reasons for exclusion of KPIs are explained. The ranking and mean value of the KPIs are also presented. The applicability of the shortlisted KPIs will further be evaluated by surveys in a later stage.

4.2 Background of the focus group study

To explore experts' point of view on retrofit key performance indicators, a focus group study was held with experienced FM professionals. The data was also more representative because of "their languages and concepts, their frameworks for understanding the world" (Wilkinson, 1998). Typical type of retrofit projects was the main focus of the focus group discussion. The objective of this focus group study is:

1. To explore experts' point of view on different building retrofit parameters for retrofitting of commercial buildings.
2. To shortlist the most useful key performance indicators (KPIs) identified from the above literature review process.
3. To investigate the importance and other feasible assessing criteria in assessing building retrofit performance.

A focus group approach was adopted because it could allow participants to explore and examine each other's point of view (Ritchie and Lewis, 2003). Data collected from the meeting will be of high quality because the respondents are under the pressure of further elaborating their opinions or challenged by other group members (Merton, 1987, Wilkinson, 1998). It will be convened to probe into the underlying assumption and answers of respondents at necessary depth and collect the richest possible information (Minichiello and Kottler, 2010). Commercial buildings can be classified into distinct gradings (e.g. Grade A-C in Hong Kong) with single/multiple ownership (Rating and Valuation Department, 2020).

<u>Section 0—Invitation and Background</u>

The optimal size of a focus group is typically between six to 12 members (Fern, 2001, Kamberelis and Dimitriadis, 2005, Stewart *et al*., 2007) for maximum interaction and input provided from them (Dennis *et al*., 2013). The focus group members were selected on the basis of: (i) FM professionals who had worked on various building types with a minimum of tactical grade, (ii) well experienced in the facility management field (e.g. >20 years work experience). It was also preferred to select small portion of participants with fewer work experience (e.g. < 20 years) in order to explore different point of view in a wider horizon. As all participants had FM work experience in Hong Kong, they could easily identify the KPIs and suggest other suitable parameters related to retrofit.

<u>Section 1— Introduction/Preparation</u>

To measure how effectively a retrofit project is performed, 62 KPIs from literature were identified and consolidated into 52. KPIs were then divided and grouped into four aspects (namely economic, environmental, health and safety, and users' perspective) for discussion during the focus group study. A questionnaire list was sent to the participants six days prior to allow them got more familiar with the questionnaire's contents before discussion at the meeting.

At the beginning of the focus group meeting, the moderator (who is experienced in FM) explained the purpose of the study, ground rules (e.g. allowance to provide any suggestions and share of their experience) and assurance the confidentiality of the discussion. During the meeting, the participants were guided to refer to the explanation stated in the appendix with application examples to facilitate their discussion (Appendix A) and avoid misinterpretation of definitions.

Section 2—Focus Group Discussion

Data of the focus group study was collected by: (i) requesting each participant to fill out a printed copy of questionnaires, (ii) recording the oral discussion of the participants, and (iii) immediate note taking of the matter discussed. The questionnaire comprised of three sections. First section requests the participants to provide personal details such as their employer (government, non-government public organization or private company), professional qualification and highest academic qualification. The second section ask participants to indicate the relative importance rating of KPIs on the questionnaires for four aspects: economic, environmental, health and safety, and users' perspective. A five-point Likert scale (*1: very low; 2: low; 3: moderate; 4: high; 5: very high*) was used. The reasons for exclusion of KPIs were written on questionnaires for them to choose such as "no record data", "too time consuming to work out", "too costly to work out" or other specific reasons. For each of the listed indicators, the moderator also facilitated the participants to vote on whether the KPIs should be included in the building retrofit evaluation. The votes were counted twice to ensure the reliability of the data. At the final section of the discussion, the participants could provide further comment and suggest any suitable indicators for assessment building retrofit.

Ten FM experts participated in the focus group meeting, which held for two and a half hours with an interim break. Seven of them were from private companies and three of them were from non-government public organizations. In the focus group, there were three directors, five managers and two assistant managers with experience (seven to 42 years) in managing the O&M works for buildings. Majority of the participants were veteran - 80% of participants have over 20 years work experience and all the participants possessed a master's degree. Being O&M professionals, they all were corporate members of the Building Services Operation and Maintenance Executives Society (BSOMES) – the leading professional institution in Hong Kong specialized in O&M works for buildings. The type of commercial buildings that they have worked on included office (80%), retail (70%), hotel (10%) and others (e.g. public infrastructure, lab, composite, exchange/data centre, railway station and ancillary building.) Table 4.1 shows the demography of the focus group members.

Table 4.1 Demography of the focus group members

Characteristic	Subgroup	Number	Percentage
Working experience in FM industry in years	<10	1	10%
	10 -20	1	10%
	20-30	6	60%
	>30	2	20%
Employer	Private	7	70%
	Non-government organization	3	30%
Job Title	Director	3	30%
	Manager	5	50%
	Assistant Manager	2	20%
Buildings/premises that have worked on	Office	8	36%
	Retail	7	32%
	Hotel	1	5%
	Others	6	27%
Professional qualification	BSOMES	10	28%
	HKIE	9	22%
	CIBSE	7	17%
	ASHRAE	4	10%
	HKIFM	1	2%
	IFMA	5	12%
	Others	5	12%

4.3 Results and KPIs selected via focus group study

4.3.1 Consolidation, naming and addition of indicators

During the focus group meeting, three new indicators were added to the questionnaires from the discussion. There was one new KPI for Economic aspect - "*E17* Increase of building value (%)*". From a detailed examination of four large Toronto commercial office building retrofit cases using pre- and post- retrofit energy and financial data (Carlson and Pressnail, 2018), it revealed that energy retrofitting buildings can decrease operating costs, increase occupancy rates, and increase effective rent (rental revenue) and therefore increasing net operating income. The market value can be increased from energy class upgrade and the external look improvement. The extraordinary maintenance impact on the property values in the real estate market was studied by Mecca, Umberto *et al*. (2020). The average after-intervention selling price per unit area was calculated. Increase in the average price of the pre-intervention sales by 25% was partly due to whole building energy efficiency upgrading, expected improvement in the look and maintenance status of its facades, and specifically 10% of apartment price increase due to energy rating jump (e.g. from F to A rating). Another increase of 15% due to improvement in the general state of preservation and maintenance in the buildings.

Two new KPIs for Environmental aspect were also included. They are "*En17* Target Green Building Label*" (such as BEAM PLUS) and "*En18* Reduction of water consumption*". The actual performance of a building and its facility management practices can be evaluated by BEAM Plus Existing Buildings (EB), covering all aspects of management, operation and maintenance, and may be initiated at any time during a building's operational life (Hong Kong Green Building Council, 2020). It helps achieve the target of the Hong Kong Government's stated Energy Saving Plan by 2025, and also encouraged more participation by the 42,000 existing buildings in Hong Kong, thus improving their energy efficiency and enhancing their environmental management practices. On the other hand, water conservation is also another important concern. Water efficiency labelling scheme and best practice guidelines were developed to the industry practitioners to implement water use efficiency measures in their daily operation. A water efficiency checklist can be used to facilitate regular water audits for assessment of water use performance (Water Supplies Department, 2020). The impact of energy performance certificates on the value of commercial property assets was studied by considering both two KPIs "*E17* Increase of building value (%)*" and "*En17* Target Green Building Label*" (Fuerst and McAllister, 2011).

For the Health and Safety aspect, name of the KPIs was renamed by adding "Ratio of" in front for clearer illustration. For example, "*HS 1* Ratio of actual to target no. of statutory orders removed (%)" was renamed from "Actual over target in removal of statutory orders". "*HS 2* Ratio of actual to target no. of accidents per year reduced (%)" was renamed from "Actual/target in reduction of number of accidents per year" for easier and clearer understanding.

For the Users' Perspective, "*U8 Internal Air Quality*" was renamed into "*U8* Target Indoor Air Quality (IAQ) class*" to suit the local practice. There are different classes of IAQ, i.e. Good or Excellent Class certified by the Environmental Protection Department (EPD). All EPD's eligible premises have joined the IAQ Certification Scheme were assessed regularly. As of 2017, sixteen offices and visitor centres attained the "Excellent" or "Good" IAQ Class (Environmental Protection Department, 2017). It was suggested to use local standard or indicators that applicable to the situation and make comparison with another similar project. Also, they stated that simple indicator can allow easier and mutual understanding for getting more funding and support on retrofit project or asset replacement project. For easier understanding, these KPIs were also renamed: "*U11 Visual comfort –Δ workplane illuminance (lux)*" revised as "*U11*Target Work plane illuminance (lux)*", and "*U12. Acoustic comfort –Δ nosie level (Leq - equivalent continuous weighted sound pressure level (dBA))*" revised as "*U12*Target Equivalent continuous weighted sound pressure level (dBA)*".

4.3.2 Shortlisted KPIs

The overall results including the mean rating, number of votes for inclusion of the KPIs in the assessment are shown in Table 4.2. 19 KPIs were shortlisted (highlighted in Table 4.2) with more than 50% agreement (at least six votes). They were identified to have a mean value of equal or more than 4.00 and within the rank ≤ 21.

The overall mean of all KPIs was 3.66, indicating the respondents weighted the indicators, on average, as important. The mean value varied from 1.90 for *"E5. Weighted Average Cost of Capital (%)*", to 5.00, "*HS1. Actual/target in removal of statutory orders*". There were 23 indicators that had mean => 4.00, which means they were very important.

Table 4.2 Summary findings from focus group (extracted from Ho *et al.*, 2021)

Aspect	No.	KPIs	Mean[a]	Rank	Vote[b]	Shortlisted[c]
Econ.	E1	Payback Period (year)	4.80	2	10	Yes
	E2	Return on Investment (%)	4.10	17=	6	-
	E3	Internal rate of return (%)	4.20	13=	6	-
	E4	Net present value ($)	3.70	27=	4	-
	E5	Weighted Average Cost of Capital (%)	1.90	56	1	-
	E6	Peak demand savings ($)	2.30	54=	0	-
	E7	Mean cost of intervention saved ($/kWh)	2.90	46=	2	-
	E8	Annual energy cost savings($/year)	4.30	10=	5	-
	E9	Profit ($)	4.00	21=	4	-
	E10	Net Cash Flow ($/year)	3.70	27=	5	-
	E11	Investment cost ($)	4.70	3=	9	Yes
	E12	Normalized investment cost ($/m^2)	4.20	13=	8	Yes
	E13	Retrofit and operation costs ($)	4.10	17=	2	-
	E14	Global Cost ($/m^2)	3.70	27=	1	-
	E15	Life Cycle Cost ($)	4.70	3=	8	Yes
	E16	Revocability Cost ($)	3.50	31=	0	-
	E17*	Increase of building value	4.30	10=	8	Yes
Enviro.	En1	CO_2 emission payback periods	2.60	52	1	-
	En2	Global warming potential	2.90	46=	0	-
	En3	Emission class indices	3.20	42=	0	-
	En4	Energy generation (%)	3.90	24	5	-
	En5	Energy payback periods	4.60	6	8	Yes
	En6	Reduction of electrical peak demand (%)	3.70	27=	4	-
	En7	Reduction of peak cooling load (%)	3.40	36	4	-
	En8	Energy consumption class	2.30	25=	0	-
	En9	Total site energy (GJ)	3.30	54=	2	-
	En10	Life Cycle Analysis	3.30	37=	5	-
	En11	Δ Carbon emission (%)	3.20	42=	4	-
	En12	Δ Carbon emission (kg$CO_{2\text{-}eq}$/m^{2}year)	3.50	31=	5	-
	En13	Energy savings (%)	4.40	8=	8	Yes
	En14	Normalized energy savings (kWh/m^{2}year)	4.00	21=	6	Yes
	En15	Δ Electricity consumption per year (kWh/year)	4.40	8=	7	Yes
	En16	Δ Normalized energy consumption (kWh/m^{2}year)	3.80	25=	4	-
	En17*	Green Building Label	4.70	37=	10	Yes
	En18*	Reduction of water consumption	3.30	3=	5	-
Health & Safety	HS1*	Ratio of actual to target number of statutory orders removed (%)	5.00	1	10	Yes
	HS2*	Ratio of actual to target in reduction of number of accidents per year reduced (%)	4.10	17=	10	Yes
	HS3*	Ratio of actual to target number of legal cases per year (%)	4.10	17=	5	-
	HS4*	Ratio of actual to target number of compensation cases per year (%)	3.50	31=	3	-
	HS5*	Ratio of actual to target in reduction in amount of compensation paid per year	3.30	37=	4	-
	HS6*	Ratio of actual to target in reduction in number of health and safety complaints per year	3.50	31=	5	-
	HS7*	Ratio of actual to target in reduction in number of lost workdays per year	3.30	37=	3	-
	HS8*	Ratio of actual to target in reduction in number of incidents of specific disease per year	3.50	31=	5	-
Users' Persp.	U1	Δ Predicted Mean Vote (PMV) index	2.80	49=	0	-
	U2	Δ Predicted Percentage of Dissatisfied (PPD) (%)	2.80	49=	0	-
	U3	Target Indoor air temperature (°C)	4.00	21=	8	Yes
	U4	Δ Discomfort hours in summer (%)	2.70	51	1	-
	U5	Thermal comfort level	3.10	45	1	-
	U6	Δ Ventilation and infiltration rates (h^{-1})	2.90	46=	2	-
	U7	Δ Indoor CO_2 levels/ other harmful substances (ppm)	4.20	13=	7	Yes
	U8*	Target IAQ class	4.50	7	10	Yes
	U9	Work productivity	3.20	42=	0	-
	U10	Δ Workforce performance (dollars/m^2)	2.30	53	0	-
	U11*	Target Work plane illuminance (lux)	4.20	13=	9	Yes
	U12*	Target Equivalent continuous weighted sound pressure level (dBA)	4.30	10	9	Yes

a: Mean of importance rating (1-5);
b: Number of votes agree to include that specific KPIs in building retrofit evaluation;
c: Shortlisted KPIs with voting > 50% agreement (i.e. at least six votes);
*: Newly added/rename of KPIs during focus group meeting.

To summarize, the relative importance categories of KPIs in matrix form is shown in Figure 4.1 and those KPIs with mean score ≥4.00 are regarded as high importance.

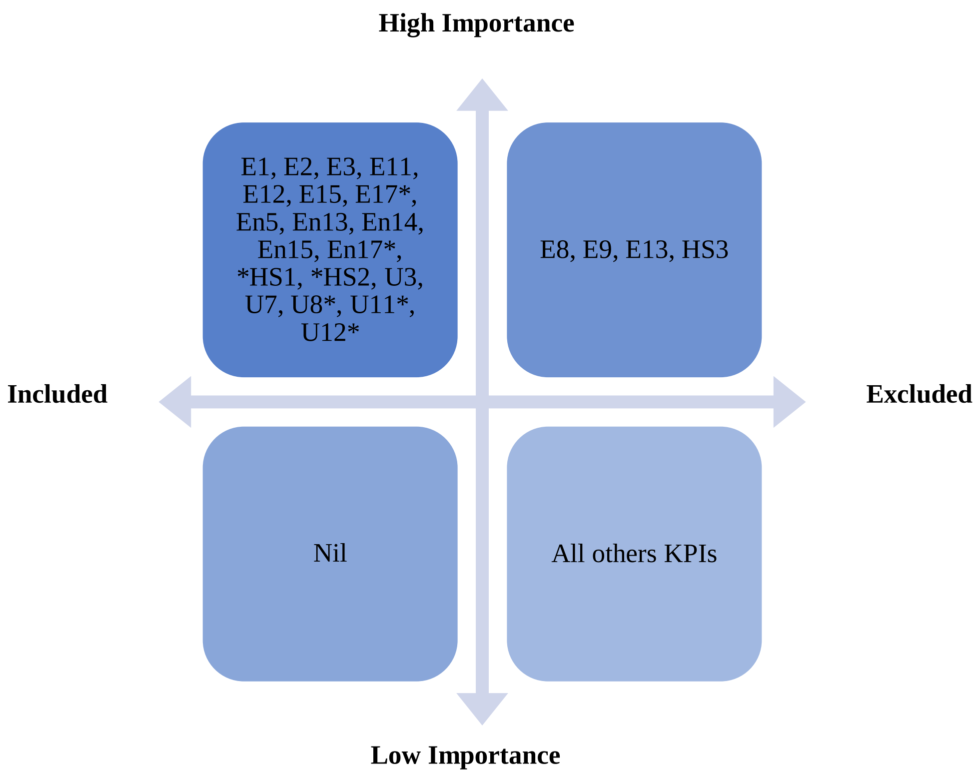


Figure 4.1. Categorization of KPIs in matrix form (extracted from Ho *et al*., 2021)

4.3.3 Excluded KPIs

Total 32 KPIs were removed during the focus group study due to "no record data", "too time consuming to work out", "too costly to work out" or other specific reasons by using the similar approach in Lai and Man, 2018b. The interactions between the reasons for exclusion are visualized in Figure 4.2.

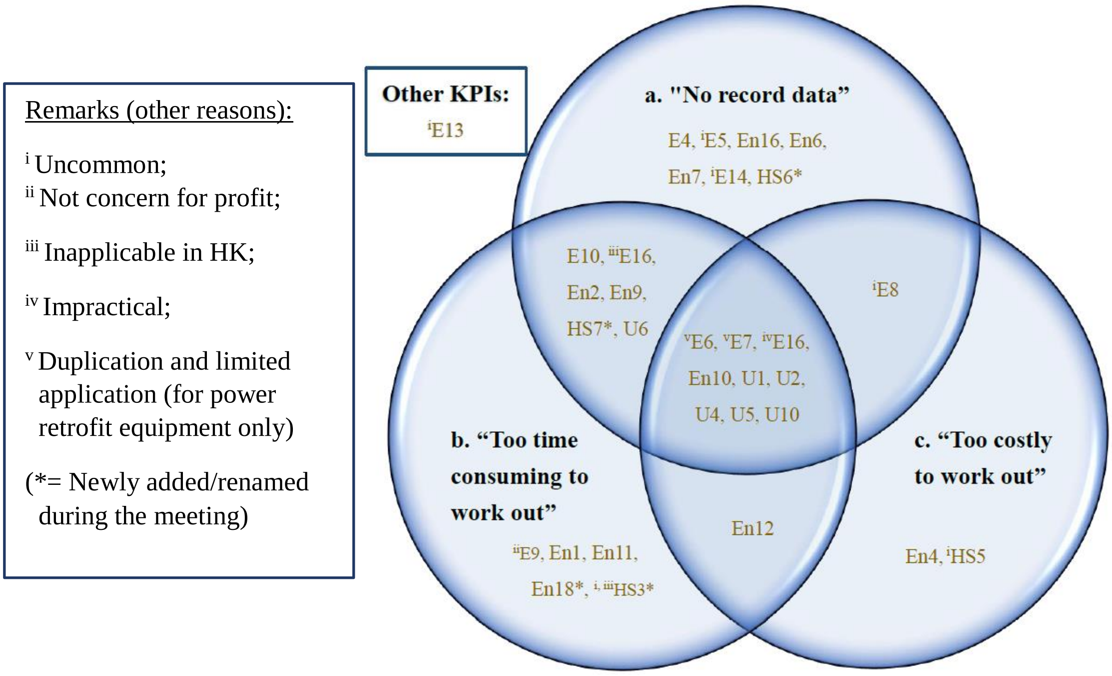


Figure 4.2. Reasons for exclusion of KPIs (extracted from Ho *et al.*, 2021)

If evaluate all the identified indicators in literature reviews, it will require considerable effort and laboring cost/workload to record and process all the needed data for evaluation. To evaluate the retrofit performance efficiently, the non-essential indicators will be removed through an industry-wide survey and consolidate their opinions in a later stage.

Despite its high ranking and mean importance score, "*E8 Annual energy cost savings ($/year) (rank: 10, mean score: 4.30)*" was excluded due to "no record data, too costly to work out and not usually used". This is especially true for existing buildings where sub-meters were not installed to monitor the energy consumption of different parts of a building services system. For example, a typical air-conditioning system for a commercial building comprises a central chiller plant and a distribution system made of components including chilled water pipes and air ductwork. Without a sub-meter for the central chiller plant, the actual energy saving resultant from the implementation of a retrofitting work for the chiller plant could not be measured or recorded (c.f. Lai *et al*. (2008)). Even if it is possible to add a sub-meter for the chiller plant, the addition cost is often high because of the work needed to modify relevant circuits of the existing system. It can be replaced by another KPI "*En1 energy saving (%)*" which has a similar meaning but represented by energy units. "*E13 Retrofit and operation costs ($) (rank 17, mean score=4.10)*" was excluded due to "not usually used". Other shortlisted KPIs which gives a similar presentation includes "*E11 Investment cost ($)*", "*E12 Normalized investment cost ($/m^2)*" and "*E15 Life cycle cost ($)*". "*HS3 Actual/target in reduction of number of legal cases per year (rank 17, mean score=4.10)*" was excluded for reasons of "too time consuming to work out, uncommon and inapplicable in practice". A lot of time and works are needed to work out the direct and indirect effect resulting from reduction of legal cases due to retrofitting. In fact, all retrofit projects must abide by the law, and this is a minimum requirement for attaining the legal requirement. "*E9 Profit*" also got a high and superior mean scoring of 4.00, was excluded because it is too time consuming to work out and profit is not a concern to practitioners who focus on technical matters. The profit resulting from the retrofitting can be difficult to work out as mentioned above from the aspect of energy cost saving, or not result in the increase in tenant rent.

4.3.4 Different perceptions of different groups

Typically, there are different levels (strategy, tactical and operational) in an FM team and their focus areas of performance evaluation are different (Lai and Yik, 2006). The different perceptions on importance level of KPIs between the directorate grade and managerial grade are compared and shown in Table 4.3. For the difference >20%

between groups, it is equivalent to >1.00 score difference out of scoring of 5.00 with high disparity.

For economic aspects, there is very high disparity (-28.57%) between the directorate grade (score = 3.00) and managerial (score = 4.43) grade for "*E9 Profit ($)*". The directorate grade may perceive carry out retrofit projects are not mainly for profit making, but for attaining other indirect benefits such as improve of company's image, increase of building value (score = 4.67). With regarding to money profit, they paid much more attention to other KPIs such as "*E3 investment cost ($)*" (score = 5.00) and "*E15 life cycle cost ($)*" (score = 4.67). For managerial grade, they may pay more attention to the profit arising from the improvement of equipment performance resulting in cost saving from the retrofit.

For environmental aspect, there is high disparity between directorate grade (score = 4.33) and managerial grade (score = 3.00) for "*En7 Reduction of peak cooling load (%)*". It may be due to higher concern of the indirect benefit of reduction of peak load by the directorate grade (i.e. reduce an additional cost for installment of equipment plant as the equipment can work at a higher working efficiency of equipment in full load condition). For managerial grade, they may less emphasis on the cost saving from new additional plant.

For health and safety, there is a high disparity between directorate grade (score = 4.00) and managerial grade (score = 3.00) for "*HS5* Ratio of actual to target in reduction in amount of compensation paid per year*". From directorate grade, they may relatively pay more concern for companies' financial interest than the managerial grade and perceive high importance for undertaking retrofit measures that help to reduce the compensation paid for the employee.

For users' perspective (Table 4.3), there is a high disparity between directorate grade (score = 3.00) and managerial grade (score = 4.43) for the KPI "*U3Target Indoor air temperature (^{o}C)*". From directorate grade point of view, they may be easier to adjust the set point room temperature for comfort in their own individual partitioned room and more frequently to work in different locations (e.g. business meeting with various parties in different locations). For managerial grade, they may need to share the common working areas with other colleagues, with less control for the set point air temperature.

4.3.5 Distribution of the KPIs

Table 4.4 summarizes the distribution of the selected indicators. To minimize the disparity problem, the shortlisted indicators had more than 50% agreement (at least six votes) and they all had an importance score of at least 4.00 (high level of importance). The 19 indicators selected are listed in Table 4.5. The dominant aspect is economic, which covers seven indicators (37%). Both the environmental and users' perspective aspects contain five indicators (26%). There are two indicators in the health and safety aspect (11%).

Table 4.3 Perception from directorate and managerial grade from focus group

Aspect	No.	KPIs	Directorate Mean[a]	Managerial Mean	Δ [b]
Econ.	E1	Payback Period (year)	5.00	4.71	5.71%
	E2	Return on Investment (%)	4.00	4.14	-2.86%
	E3	Internal rate of return (%)	4.33	4.14	3.81%
	E4	Net present value ($)	3.67	3.71	-0.95%
	E5	Weighted Average Cost of Capital (%)	2.33	1.71	12.38%
	E6	Peak demand savings ($)	2.00	2.43	-8.57%
	E7	Mean cost of intervention saved ($/kWh)	2.33	3.14	-16.19%
	E8	Annual energy cost savings($/year)	4.33	4.29	0.95%
	E9	Profit ($)	3.00	4.43	-28.57%
	E10	Net Cash Flow ($/year)	4.00	3.57	8.57%
	E11	Investment cost ($)	5.00	4.57	8.57%
	E12	Normalized investment cost ($/m^2)	4.33	4.14	3.81%
	E13	Retrofit and operation costs ($)	4.33	4.00	6.67%
	E14	Global Cost ($/m^2)	4.00	3.57	8.57%
	E15	Life Cycle Cost ($)	4.67	4.71	-0.95%
	E16	Revocability Cost ($)	3.67	3.43	4.76%
	E17*	Increase of building value	4.67	4.14	10.48%
Enviro.	En1	CO_2 emission payback periods	2.33	2.71	-7.62%
	En2	Global warming potential	3.33	2.71	12.38%
	En3	Emission class indices	3.00	3.29	-5.71%
	En4	Energy generation (%)	4.33	3.71	12.38%
	En5	Energy payback periods	4.33	4.71	-7.62%
	En6	Reduction of electrical peak demand (%)	4.33	3.43	18.10%
	En7	Reduction of peak cooling load (%)	4.33	3.00	26.67%
	En8	Energy consumption class	1.67	2.57	18.10%
	En9	Total site energy (GJ)	3.33	3.29	0.95%
	En10	Life Cycle Analysis	2.67	3.57	18.10%
	En11	Δ Carbon emission (%)	3.00	3.29	-5.71%
	En12	Δ Carbon emission (kg$CO_{2\text{-}eq}$/m^{2}year)	3.67	3.43	4.76%
	En13	Energy savings (%)	4.33	4.43	-1.90%
	En14	Normalized energy savings (kWh/m^{2}year)	4.00	4.00	0.00%
	En15	Δ Electricity consumption per year (kWh/year)	4.67	4.29	7.62%
	En16	Δ Normalized energy consumption (kWh/m^{2}year)	4.00	3.71	5.71%
	En17*	Green Building Label	5.00	4.57	8.57%
	En18*	Reduction of water consumption	3.00	3.43	-8.57%
Health & Safety	HS1*	Ratio of actual to target number of statutory orders removed (%)	5.00	5.00	0.00%
	HS2*	Ratio of actual to target in reduction of number of accidents per year reduced (%)	3.67	4.29	-12.38%
	HS3*	Ratio of actual to target number of legal cases per year (%)	4.33	4.00	6.67%
	HS4*	Ratio of actual to target number of compensation cases per year (%)	3.67	3.43	4.76%
	HS5*	Ratio of actual to target in reduction in amount of compensation paid per year	4.00	3.00	20.00%
	HS6*	Ratio of actual to target in reduction in number of health and safety complaints per year	3.00	3.71	-14.29%
	HS7*	Ratio of actual to target in reduction in number of lost workdays per year	3.00	3.43	-8.57%
	HS8*	Ratio of actual to target in reduction in number of incidents of specific disease per year	3.33	3.57	-4.76%
Users' Persp.	U1	Δ Predicted Mean Vote (PMV) index	2.00	3.14	-22.86%
	U2	Δ Predicted Percentage of Dissatisfied (PPD) (%)	2.33	3.00	-13.33%
	U3	Target Indoor air temperature (^oC)	3.00	4.43	-28.57%
	U4	Δ Discomfort hours in summer (%)	3.00	2.57	8.57%
	U5	Thermal comfort level	2.67	3.29	12.38%
	U6	Δ Ventilation and infiltration rates (h^{-1})	2.33	3.14	16.19%
	U7	Δ Indoor CO_2 levels/ other harmful substances (ppm)	3.67	4.43	15.24%
	U8*	Target IAQ class	4.33	4.57	-4.76%
	U9	Work productivity	3.33	3.14	3.81%
	U10	Δ Workforce performance (dollars/m^2)	2.33	2.29	0.95%
	U11*	Target Work plane illuminance (lux)	4.00	4.29	-5.71%
	U12*	Target Equivalent continuous weighted sound pressure level (dBA)	4.33	4.29	0.95%

a: Mean of importance rating (1-5); b: Positive means directorial grade perceived that KPIs more important than managerial grade. Negative means managerial grade perceived that KPI more important than directorial grade.

Table 4.4. Distribution of the selected indicators

Aspect	No. of shortlisted KPIs	Percentage (%)
Economic	7	37%
Environmental	5	26%
Health and Safety	2	11%
Users' Perspective	5	26%
Total	19	100%

Table 4.5 Selected performance indicators

No.	Indicator
E1	Payback period (year)
E2	Return on investment (%)
E3	Internal rate of return (%)
E11	Investment cost ($)
E12	Normalized investment cost ($/m^2)
E15	Life cycle cost ($)
E17*	Increase of building value
HS1*	Ratio of actual to target number of statutory orders removed (%)
HS2*	Ratio of actual to target number of accidents per year reduced (%)
En5	Energy payback periods (years)
En13	Energy savings (%)
En14	Normalized energy savings (kWh/m^{2}year)
En15	Δ Electricity consumption per year (kWh/year)
En17*	Green building label
U3	Target indoor air temperature (^{o}C)
U7	Δ Indoor CO_2 levels/ other harmful substances (ppm)
U8*	Target IAQ class
U11*	Target workplane illuminance (lux)
U12*	Target equivalent continuous weighted sound pressure level (dBA)
*: Newly added/rename of KPIs during focus group meeting.	

Table 4.6 Examples of application of the identified KPIs to previous case studies (extracted from Ho *et al.* 2021)

Authors (year)	Place (building type)	Indicators	Application
Jankovic (2019)	UK (residential)	E13 - Energy savings (%); U7 - Δ Indoor CO_2 levels	Analyzed heating energy demand and internal air quality after retrofitting the existing mechanical ventilation system
Liu et al. (2015)	Sweden (residential)	U3 - Target indoor air temperature (°C); U7 - Δ Indoor CO_2 levels; U12* - Target equivalent continuous weighted sound pressure level (dBA); En15 - Δ Electricity consumption per year (kWh/year)	The results show that the building has potential to reach more than one-third reduction of space reduction demand. Improvement on indoor air quality, temperature, noise situation and health-related problems were found by questionnaire (e.g. "too cold during winter", "varied room temperature" and "draught" are the three biggest problems in non-retrofitted building).
Carlson and Pressnail (2018)	Canada (commercial)	E17* - Increase of building value (%)	Energy retrofitting can decrease building operating costs, increase occupancy rates and increase rental revenue, thereby increasing net operating income. The market value of the building was also increased.

Although Table 4.5 reveals that in terms of number of indicators, the economic aspect prevailed, it does not necessarily mean that this aspect represents the majority share when the performance of building retrofits is evaluated using the selected indicators. For illustration purposes, Table 4.6 lists some examples of application of the identified KPIs to previous case studies.

Some of the selected economic indicators have overlapping in their meanings. For "*E1 Payback period*", it can answer whether the retrofit project is worth to invest in. Data needed for calculating for this indicator include cost of the retrofit project and energy saving after completion of the project. Such data are also required in whole or in part when calculating other economic indicators such as potential energy saving and life cycle cost, as in the study of Mahlia *et al*. (2011). The T5 system was found to be a more suitable lighting retrofit as compare with T8 electronic and HPT8 system in campus buildings of the University of Malaya, Malaysia. Therefore, further work is needed to investigate whether it is necessary to combine some of those indicators with overlapped meanings.

For "*E11 Investment Cost ($)*" and *"E12 Normalized investment cost (\$/m²)*", they are two indicators with similar meaning. The main difference between them is that the former indicator counts only the amount of cost invested while the latter calculates that amount on a unit area basis (i.e. normalization). In practice, both indicators can be used for comparison or benchmarking purposes, depending on the angle from which the performance of the concerned retrofit project is evaluated. To determine whether one of these two indicators should be taken for eventual use in evaluating building retrofit performance, further investigation is required. The levelized cost of saved energy method was developed and demonstrated on a housing stock in Italy (Filippi *et al.*, 2020). Through doubling of current investments, about 60% baseline energy consumption can be saved. By over three times the current investments, a maximum saving of 75% energy consumption can be achieved.

For "*En17 Green Building Label*" such as BEAM Plus, credits were allocated by taking into account of other internationally recognized green buildings and its environmental performance (e.g. consider the weighting in management, site aspects, materials and waste aspects, energy use, water use, and indoor environmental quality) (BEAM

Society Limited and Hong Kong Green Building Council, 2016). It can be used as an indicator for reflecting its improved retrofit performance in environmental aspect.

For health and safety aspect, there are only two indicators where it does not imply that this aspect is not important at all in evaluating the performance of building retrofits. Note that "*HS1* Ratio of actual to target number of statutory orders removed (%)*" was rated as the most important indicator. This indicator, if assigned with a great weighting and is taken in developing a retrofit performance evaluation scheme – similar to that for O&M performance evaluation (Lai and Man, 2017), the health and safety aspect could, to a large extent, determine the overall performance evaluation result of the concerned retrofit project. Therefore, a further stage of study should, using methods such as the Analytic Hierarchy Process or the Analytic Network Process, find out the weights of the KPIs constituting the intended performance evaluation scheme. There are many different types of statutory orders in Hong Kong. Common building defects can be occurred in various forms and all types of buildings irrespective of age, and the examples are below:

1. Spalling concrete: (i) defective concrete, spalling or loose plaster in ceilings, (ii) water seepage from external wall/window/roof/ceiling, (iii) structural cracks in walls/column/beams and (iv) defective wall finishes/tiles (Buildings Department, 2002). To solve the problems, minor concrete defects such as surface spalling can be hacked off down and patched up with appropriate repair mortars to protect the steel reinforcement from rusting. For a more serious defect that defective concrete is extensive and penetrates to the steel bars, building retrofit or even demolition is required. The Buildings Department (BD) may issue advisory, warning letters or

statutory orders to building owners to investigate and rectify defects or irregularities. Statutory orders under Section 26 of the Buildings Ordinance requires building owners or owners corporation (OC) of buildings which are found to bear serious defects likely to cause risk of injury or damage, repair works are required to render the building safe, usually the time specified within 6 months. Incompliance with the requirements may be liable to prosecution, fines and/or imprisonment (Buildings Department, 2002). Therefore, retrofitting project may help to remove the statutory orders issued by the authorities.

2. Defective sprinkler system/Complied with the Fire Safety Improvement Directions: Under Fire Safety Premises Ordinance (Chapter 502), two kinds of commercial premises, namely prescribed commercial premises (including banks, off-course betting centers, premises that require exceptionally high security measures such as jewelry, department stores and shops with an area over 230m^2) and specified commercial buildings (for those buildings that have been completed before 1st March 1987) are within the scope of this Ordinance. These old buildings are basically found to have inadequate fire service installations that may pose danger to the occupiers when there is a fire. Fire Safety Improvement Directions may be issued by the BD or the Fire Services Department, requiring upgrading and improvement of the fire service installations (e.g. adding sprinkler system, reinstatement or improvement of smoke lobby doors, fire resisting construction such as walls and openings etc.). Therefore, the removal of statutory orders on defective sprinkler system or achievement of fire safety improvement directions can be an indicator (HS2) to evaluate the improved building occupants' safety due to retrofitting (Buildings Department, 2002).

3. Removal of statutory orders on drainage repair: Water seepage and drainage nuisance are common defects in Hong Kong that causing nuisance to occupants across floors. It is very difficult to identify the source or cause of water seepage that may require extensive investigation. It can be a long process that required co-operation between parties concerned. For drainage repair, order under Section 28 of the Building Ordinance requires building owners or OC of buildings which found to bear defective or inadequate drainage installations or causing nuisance to investigate and rectify the situation (Buildings Department, 2002).

4. Removal of nuisance notice on Legionnaire's' Disease:
There is public concern about the risks of contracting legionella from the cooling towers. The Electrical and Mechanical Services Department has been regulating the water quality of freshwater cooling tower under the Public Health and Municipal Services Ordinance, Cap 132 (PHMSO) (Electrical and Mechanical Services Department, 2019). In Hong Kong, building owners and associated practitioners should follow the practical guidelines in the Code of Practice for Prevention of Legionnaires' Disease on the proper design, operation, maintenance of building facilities to prevent spread of legionella. Any cases of Legionnaire's Disease involving repair, maintenance or service of either cooling systems that use fresh water or hot water services are required to notify the Commissioner of Labour (Prevention of Legionnaires' Disease Committee, 2016). If water samples in freshwater cooling towers are found with total legionella count at or above 1000cfu/milliliter, emergency decontamination will be carried out for abatement within a prescribed period. Incompliance with the requirements of the nuisance notice is an offence under the Public Health and Municipal Services Ordinance, Cap 132 (Electrical and Mechanical Services Department, 2019). In Singapore, with respect to

different range of Legionella bacteria count (cfu/milliliter, for example (a) $\leq$10 , (b) 10 to <1000 and (c) $\geq$ 1000, their respectively action are (a) advisory letter, (b) enforcement action and (c) order under Environmental Public Health (Cooling Towers and Water Fountains) Regulation 2001 to shut down the system immediately, decontaminate, clean and follow-up (Institute of Environmental Epidemiology, 2001). Under Buildings Ordinance (Chapter 123), statutory orders may be served on owners to rectify unsafe and undesirable situations such as fire hazards, drainage nuisance, etc (Buildings Department, 2002). Therefore, the removal of statutory orders on spalling concrete can be a health and safety indicator (HS1) to evaluate the building retrofit performance.

4.4 Summary

As using excessive indicators to evaluate performance entails significant time and resources that would outweigh the benefits obtainable from the performance evaluation (Lai and Man, 2018a; b), the compiled indicators underwent a focus group study. A total of 52 indicators for evaluating building retrofit performance in commercial buildings had been identified and consolidated from the literature. The KPIs from literature were categorized into four groups (economic, environmental, health and safety, and users' perspective) and examine their importance and applicably.

The current article presented a rigorous three-session focus group meeting, who are experts in the O&M field to provide useful responses for the selection of appropriate retrofit performance indicators. Grounded upon the deliberations and opinions of the focus group experts, 19 of the indicators were selected as the KPIs for evaluating the performance of building retrofits.

The reasons for exclusion of the indicators were also revealed. It includes considerable time and resources of manual collection and retrieval of data, where the above reasons may be overcome by the advancement of building information modeling (BIM) and smart sensors in future. Among the KPIs, those (7) in the economic aspect dominate while the aspect with the smallest number (2) of indicators is health and safety. However, this finding does not corroborate the relative importance between the different aspects. As discussed, further work is needed to examine any overlapped meaning of KPIs and further determine the weights of the indicators that constitute the intended performance evaluation scheme.

Chapter 5 – Further shortlisting KPIs via surveys

5.1 Introduction

In this chapter, selection of 19 essential KPIs among the 52 applicable performance indicators identified from the literature and focus group, was taken to design a questionnaire survey. The method for data collection, analyses of the survey data (e.g. background of the survey participants, their perceived level of importance towards the KPIs, level of agreement between parties) are presented. The analyzed findings and implications of the study are also reported. The shortlisted KPIs from the survey were consolidated to make it more precise for establishing an analytic method for evaluating the performance of building retrofits in commercial buildings.

5.2 Survey process and method

Survey Components

The survey consisted of three parts (Appendix B). Part 1 collects respondents' personal information, including gender, years of work experience, job title, nature and type of their employer, types of building or premises they have worked on, and their academic qualification. These pieces of information served to reflect the backgrounds of the respondents, allowing inter-group comparisons to be made when analyzing the survey findings. Part 2 solicits the importance ratings of the 19 KPIs on a five-point scale (*1: very low; 2: low; 3: moderate; 4: high; and 5: very high*). Part 3 asks the participants to suggest any other KPIs they consider important and any other comments they have based on their experience.

Pilot Test

Five pilot tests, with the participation from five FM experts, were conducted on the questionnaire. These tests helped to detect and eliminate any potential error or misunderstanding of the questions in the survey. Feedbacks (such as re-written the questions in survey to become more reader friendly) from the tests were taken to finalize the questionnaire before its official distribution.

Survey Distribution and collection

The industry-wide online survey was officially launched in two ways: snowballing and mass mail. Although the snowball sampling method is hardly used to reflect a large study population, it is still a useful way to support a preliminary exploration in the studied area (Man *et al*., 2015). In the first way, FM professionals who participated in the preceding focus group study (Ho *et al*., 2021) were invited to complete the survey and distributed it to their colleagues. In the second way, a hyperlink to the survey was emailed to all members of the Building Services Operation and Maintenance Executives Society (BSOMES) – the leading professional body in Hong Kong with members specialized in technical FM works embracing building retrofitting. In order to increase the level of representativeness of the samples, FM practitioners with different organization natures (government, non-governmental organization and private company) and types (e.g. owner/developer, management company, contractor) working at different levels (strategic (e.g. director, chief engineer), tactical (e.g. manager, engineer)) were invited to participate in the survey.

Profile of the participants

A total of 164 responses to the survey were received. To ensure data quality, the responses were screened manually and those with incomplete information provided were discarded. This resulted in having 124 responses qualified for the subsequent data analysis, representing a 40% response rate. The demographic details of respondents were shown in Table 5.1. Among these responses, most (83.9%) came from males. The majority of the respondents were highly experienced; most of them were employed by private companies. The proportions of those working for owners/developers and management companies were comparable while those working for contractors amounted to 14.5%. When compared between the strategic and tactical groups, the latter prevails. More than three quarters of the participants have worked on office buildings; nearly half have worked on retail premises. The respondents were well educated, with most of possessing a degree at the bachelor level or above. Half of the respondents were members of the Hong Kong Institution of Engineers (HKIE), which is a professional body of engineers in Hong Kong. Nearly half of respondents were corporate members of the Building Services Operation and Maintenance Executives Society (BSOMES) – the leading professional institution in Hong Kong specialized in O&M works for buildings. About one-third respondents are corporate members in the Chartered Institution of Building Services Engineers (CIBSE), and about 5% were member of the Hong Kong Institute of Facility Management (HKIFM).

Table 5.1 Demographic details of respondents

Characteristic	Subgroup	Number	Percentage
Gender	Male	104	83.9%
	Female	20	16.1%
Working experience in FM industry in years	≤5	22	17.9%
	>5 to <20	21	17.1%
	20 to <30	39	31.7%
	≥30	41	33.3%
Employer	Government	11	8.9%
	Non-government public organization	23	18.6%
	Private company	90	72.6%
Role of current employer	Owner/developer	43	34.7%
	Management company	44	35.5%
	Contractor	18	14.5%
	Others	19	15.3%
Job Level	Strategic level	38	30.7
	Tactical level	86	69.4
Buildings/premises that have worked on	Office	94	75.8%
	Retail	61	49.2%
	Hotel	31	25.0%
	Others	54	43.6%
Professional qualification (Corporate class or above)	BSOMES	56	45.2%
	HKIE	62	50.0%
	CIBSE	43	34.7%
	HKIFM	6	4.8%
	Others	42	33.9%
Highest academic qualification	Associate degree / diploma / certificate	7	5.6%
	Bachelor degree	32	25.8%
	Master degree	81	65.3%
	Doctorate degree	2	1.6%
	Others	2	1.6%

5.3 Data Analysis

Data were analyzed using SPSS Version 26. Group analyses were completed using Kruskal-Wallis H-test (H-test) and Mann−Whitney U-test (U-test) to analyze the different perceptions on importance levels of KPIs from respondents. α values for both tests were set with p-values less than 0.05. Spearman Rank Correlation was applied to investigate the significant difference of rank obtained between groups (G1-G6), and finally a relative important index, mean score and rank of each KPIs were computed to shortlist the most essential KPIs. Respondents were stratified into six main groups (G1-G6) and sub-groups (n_1, n_2, n_3, n_4) as follows:

- G1: Gender: male (n_1=104) and female (n_2=20).
- G2: FM/Operation and Maintenance (O&M) work experience: <5 years (n_1=22), 5 years to < 20 years (n_2=21), 20 to < 30 years (n_3=39), and ≥30 years (n_4=42).
- G3: Nature of organization that the respondents worked at: government (n_1=11), public (n_2=23) and private (n_3=90).
- G4: Employer: owners/developers (n_1=43), management companies (n_2=44), contractors (n_3=18) and others (n_4=19).
- G5: Job level: strategic (n_1=38) and tactical (n_2=86).
- G6: Academic qualification: sub-degree (associate degrees/diplomas/certificates), bachelor (n_1=41), and postgraduate (master's degrees or doctorate degrees) (n_2=83).

To investigate the difference in perception of KPIs by respondents, this study splits the sample into groups and compared by H-test and U-test. H-test is a nonparametric test that compares more than two independent or unrelated samples (Corder *et al*., 2014, Weaver et al., 2017) and it was applied to make comparison with the subgroups "G2: FM/O&M work experience", "G3: nature of organization" and "G4: role of employer". As H-test does not identify where, and the degree of the differences occurred, post hoc tests such as U-test was used to analyses any significant differences between the specific sample pairs. For the subgroups "G1: gender", "G5: job level" and "G6: academic qualification", "male vs female", "strategic vs tactical", "bachelor and below vs postgraduate and above" were compared by U-test. The U-test is a non-parametric test that can be used to compare two unrelated or independent samples and does not require the two variables to be of equal sample size (Corder *et al.*, 2014, Weaver *et al.*, 2017). Therefore, it is suitable to use in comparison of two groups in the present study.

5.3.1 Kruskal-Wallis H-test

The Kruskal-Wallis H test is a nonparametric statistical test that compares more than two independent or unrelated samples (the dependent variable can be ordinal or interval/ratio in nature) (Corder *et al*., 2014, Weaver *et al*., 2017). The level of risk (α) is set at 0.05, where 95% change that any observed statistical difference will be real and not due to chance. A Kruskal-Wallis H test statistic was determined by equation (5.1).

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \qquad \text{(eq.5.1)}$$

where N is the number of values from all combined samples, R_i is the sum of the ranks from a particular sample, and n_i is the number of values from the corresponding rank sum. The degrees of freedom, df, in the Kruskal-Wallis *H*-test are determined by equation (5.2).

$$df = k-1 \tag{eq.5.2}$$

where df is the degrees of freedom and k is the number of groups. SPSS computations were used to substitute the manual manipulations. For those number of groups (k) or the numbers of values in each sample (n_i) exceed those available from the table, a large sample approximation will be needed to be performed by using a table with χ^2 distribution (Corder *et al.,* 2014). For ties existed for the ranking of values, tie correction is needed and was determined by equation (5.3).

$$C_H = 1 - \frac{\Sigma(T^3 - T)}{(N^3 - T)} \tag{eq.5.3}$$

where C_H is the ties correction, *T* is the number of values from a set of ties, and *N* is the number of values from all combined samples. The corrected H (H_c) can then be found by equation (5.4), where H_o is the original H.

$$H_c = H_o/C_H \tag{eq.5.4}$$

Type I error rate will tend to become inflated when performance multiple sample contrasts and must adjust the initial level of risk. The adjusted α from the Bonferroni procedure was shown in the equation (5.5).

$$\alpha_B = \frac{\alpha}{k} \tag{eq.5.5}$$

where α_B is the adjusted level of risk, α is the original level of risk, and *k* is the number of comparisons. When H-test leads to significant results, at least one of the samples is different from others. However, it does not identify where, and the degree of the differences occurred. Therefore, other sample contrasts or post hoc tests might be used to analyses any significant differences between the specific sample pairs. Therefore, Mann–Whitney U test was used to study the sample contrasts between individual sample sets.

5.3.2 Mann–Whitney U test

The Mann−Whitney U-test is non-parametric test that can be used to compare two unrelated, or independent samples (e.g. ordinal, interval, or ratio), and does not require the two variables to be of equal sample size (Corder *et al*., 2014, Weaver *et al*., 2017). The level of risk(α) is set at 0.05, where 95% change that any observed statistical difference will be real and not due to chance. A Mann−Whitney U-test statistic for each of the two samples can be determined by equation (5.6), and the smaller of the two U statistics is the obtained value:

$$x = n_1 n_2 + \frac{n_i(n_i+1)}{2} - \sum R_i \qquad \text{(eq.5.6)}$$

where Ui is the test statistic for the sample of interest, n_i is the number of values from the sample of interest, n_1 is the number of values from the first sample, n_2 is the number of values from the second sample, and ΣR_i is the sum of the ranks from the sample of interest. For n_i exceeds the available value from the table, large sample approximation may be performed by computing a z-score and refer to the normal distribution table to obtain a critical region of z-scores (Corder *et al*., 2014). The z- score for Mann - Whitney U-test for large samples can be found by equation (5.7):

$$\overline{x_U} = \frac{n_1 n_2}{2} \quad \text{(eq.5.7)}$$

where $\overline{x_U}$ is the mean, n_1 is the number of values from the first sample, n_2 is the number of values from the second sample;

$$S_U = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}} \quad \text{(eq.5.8)}$$

where standard deviation S_U is expressed in equation (5.8);

$$z * = \frac{U_i - \overline{x_U}}{S_U} \quad \text{(eq.5.9)}$$

where z* is the z-score for a normal approximation of the data can then be found in equation (5.9), U_i is the U statistic from the sample of interest.

5.3.3 Analyzed results for H-test and U-test

Table 5.2 shows the summary tables of the U-test and H-test. First, significant difference ($U=701$, $n_1=104$, $n_2=20$, $p<0.05$) was found between male (mean rank = 59.24) and female (mean rank = 79.45) for KPI-11 (Life cycle cost ($)), revealed that the female and male FM practitioners had different perceptions on life cycle cost in evaluating the building retrofit project. This finding echoes with Rodríguez *et al.* (2017)'s argument regarding different genders' perception on managerial style: men and women have differentiated managerial styles.

Second, significant difference ($H = 10.538$, $p < 0.05$) was found between respondents with different FM/O&M work experience for KPI-2 (Normalised energy savings (kWh/m^2 year)). The results indicate that respondents ($U = 249$, $p < 0.0125$) with fewer work experience (≤5 years; mean rank = 39.18) considered KPI-2 as more important than experienced practitioners (work experience between 20 to 30 years, mean rank = 26.38) did. Similar findings were found between the freshmen and veteran (≤5 years; mean rank = 41.59) and veterans (≥30 years; mean rank = 27.74) in ranking KPI-2 ($U = 262$, $p < 0.0125$). It can be explained that the respondents with fewer work experience may always learn this KPI at their educational institution and unfamiliar with its practical applicability and hence give a higher rating to this KPI than those the veteran. Experienced practitioners were aware that after years of building occupation with energy retrofits already undertaken, the room for further energy saving is limited. Yet, no major disagreement was found between the various respondent groups (with different work experiences) on KPI-1 'energy savings (%)'. According to Miller and Higgins (2015), 'percentage better and percentage saved' was mostly referenced in environmental performance evaluation studies.

Third, a significant difference ($H = 8.726$, $p < 0.05$) was found between freshmen and non-freshman (>5 years) for KPI-13 (ratio of actual to target no. of statutory orders removed (%)). The results ($U = 125.5$, $p < 0.0125$) show that respondents with more work experience (mean rank = 27.02) considered KPI-13 as more important than the freshmen (mean rank = 17.20). The possible reason could be the freshmen may have relatively less work experience and may not have come across any retrofit projects with the requirement in statutory orders removal. Therefore, the freshmen were less concerned about this KPI.

The other significant differences were found between respondents at tactical level and strategic level. For KPI-17 (target IAQ class; $U = 1234$, $p < 0.05$); KPI-18 (target workplane illuminance (lux); $U = 1159$, $p < 0.05$); KPI 19 (target indoor equivalent continuous weighted sound pressure level (dBA); $U = 1239$, $p < 0.05$), respondents at the tactical level perceived the three KPIs (mean rank of KPI-17 = 67.15; mean rank of KPI-18 = 68.02; and mean rank of KPI-19 = 67.09) as more important than those at the strategic level did (mean rank of KPI-17 = 51.97; mean rank of KPI-18 = 50.00; mean rank of KPI-19 = 52.11). It is because respondents at the tactical level may need to perform more technical works that requires acute lighting (e.g. computer CAD drawing) and have a higher chance in sharing the common working areas, while respondents from strategical level (e.g. director) may pay more time on planning and strategies development and work at individual office with wall partitions. Apart from that, FM practitioners at tactical level handle complaints (regarding to the indoor air quality, workplane illuminance, noise etc.) and solve them before reaching to a strategic level. Hence, FM practitioners at tactical level may be more concerned on these KPIs (related to user's perspective aspect) than those from strategical level.

Table 5.2 Comparisons of responses among groups (G1-G6)

KPIs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
G1: Gender [Male (n_1=104) and Female (n_2=20)]																			
U	884.5	883.0	880.0	932.0	918.0	899.0	938.5	850.0	962.5	1000.0	701.0	1020.0	1038.0	809.5	939.5	917.0	1018.0	842.0	1010.0
p-value	0.260	0.257	0.256	0.439	0.382	0.318	0.469	0.171	0.570	0.768	**0.014***	0.885	0.989	0.097	0.455	0.364	0.873	0.145	0.824
G2: Working experience in FM/O&M of buildings [a. <5 years (n_1=22), b. 5 to < 20 years (n_2=21), c. 20 to < 30 years (n_3=39), d. ≥30 years (n_4=42)]																			
H	2.728	10.538	5.112	0.782	5.225	1.252	2.289	5.517	1.133	1.282	1.493	1.417	8.726	4.434	5.797	4.754	6.783	2.469	1.050
p-value	0.435	**0.015***	0.164	0.854	0.156	0.740	0.515	0.138	0.769	0.733	0.684	0.702	**0.033***	0.218	0.122	0.191	.079	0.481	0.789
U(a&b)	230.5	158.0	227.5	224.5	210.5	216.5	214.5	197.0	199.5	211.5	217.0	190.0	125.5	182.0	215.0	200.0	227.0	208.5	224.0
p-valu	0.990	0.061	0.929	0.868	0.602	0.712	0.673	0.374	0.413	0.609	0.720	0.283	**0.006^**	0.211	0.681	0.424	0.918	0.558	0.853
U(a&c)	371.0	249.0	361.5	375.5	320.0	359.0	336.0	285.0	414.5	373.0	378.0	422.5	405.0	396.5	353.5	385.0	289.0	389.5	388.0
p-value	0.350	**0.004^**	0.283	0.392	0.081	0.259	0.139	0.021	0.809	0.355	0.406	0.917	0.702	0.594	0.224	0.468	0.022	0.517	0.489
U(a&d)	373.5	262.0	328.0	425.5	323.5	421.5	449.0	404.0	452.5	392.0	439.0	431.5	345.0	448.0	424.5	404.0	395.0	426.0	433.0
p-value	0.182	**0.003^**	0.046	0.583	0.037	0.548	0.844	0.372	0.883	0.279	0.727	0.650	0.078	0.833	0.543	0.366	0.302	0.583	0.659
U(b&c)	353.5	379.5	351.0	376.5	343.0	373.5	365.5	346.5	365.5	395.0	341.5	344.0	271.5	282.5	315.0	314.0	289.5	322.5	353.5
p-value	0.353	0.617	0.340	0.592	0.281	0.562	0.479	0.307	0.467	0.808	0.262	0.276	**0.024^**	0.037	0.119	0.110	0.047	0.142	0.332
U(b&d)	360.0	392.5	336.5	420.5	358.0	441.0	437.0	428.0	379.0	412.5	396.5	402.0	359.0	331.0	425.5	429.5	370.0	356.0	402.0
p-value	0.210	0.455	0.114	0.754	0.206	1.000	0.951	0.842	0.337	0.656	0.494	0.550	0.198	0.092	0.793	0.855	0.268	0.174	0.539
U(c&d)	772.5	783.5	708.0	786.5	795.5	755.0	700.0	657.5	780.0	793.5	765.5	769.5	684.0	776.5	593.5	625.5	683.5	801.5	787.0
p-value	0.637	0.719	0.271	0.745	0.814	0.529	0.237	0.107	0.689	0.793	0.586	0.622	0.180	0.668	0.017	0.043	0.169	0.857	0.740
G3: Nature of organization: [a. Government (n_1=11), b. Public (n_2=23) and c. Private (n_3=90)]																			
H	0.386	1.645	0.866	0.093	0.992	1.137	0.158	1.615	4.879	0.092	1.145	0.982	1.143	1.012	0.039	2.008	4.45	4.055	4.814
p-value	0.824	0.439	0.649	0.954	0.609	0.566	0.924	0.446	0.087	0.955	0.564	0.612	0.565	0.603	0.981	0.366	0.108	0.132	0.090
G4: Role of current employer [a. Owner/developer (n_1=43), b. Management company (n_2=44), c. Contractor (n_3=18) and d. Others (n_4=19)]																			
H	2.281	2.473	0.097	4.500	6.168	0.278	0.258	1.036	1.302	2.617	0.046	3.361	3.887	0.037	1.273	0.603	7.142	2.554	1.636
p-value	0.516	0.480	0.992	0.212	0.104	0.964	0.968	0.793	0.729	0.454	0.997	0.339	0.274	0.998	0.736	0.896	0.068	0.466	0.651
G5: Job level [Strategic level (n_1=38) and Tactical level (n_2=86)]																			
U	1493.0	1550.5	1591.0	1581.5	1536.5	1411.5	1546.5	1475.0	1438.0	1441.0	1315.5	1589.0	1449.5	1475.0	1371.0	1621.0	1234.0	1159.0	1239.0
p-value	0.415	0.630	0.807	0.764	0.578	0.208	0.618	0.361	0.251	0.256	0.065	0.796	0.290	0.361	0.119	0.939	**0.021***	**0.005***	**0.019***
G6: Highest academic qualification [Sub-degree or bachelor degree (n_1=41), and Postgraduate degree (n_2=83)]																			
U	1546.0	1517.0	1637.5	1637.5	1478.0	1575.0	1626.0	1537.5	1595.5	1517.0	1617.0	1569.0	1376.0	1675.5	1541.5	1628.0	1614.0	1611.5	1637.0
p-value	0.445	0.354	0.812	0.810	0.255	0.558	0.762	0.420	0.626	0.345	0.719	0.529	0.068	0.980	0.418	0.763	0.707	0.604	0.801
Note: * Statistically significant at α = 0.05, i.e. $p \leqslant 0.05$; ^ Statistically significant at α_B = 0.0125, i.e. $p \leqslant 0.0125$																			

5.3.4 Spearman rank-order correlation

Spearman rank correlation (r_s) was applied to study the significant difference of rank obtained between two parties. The null hypothesis H_o: $\rho = 0$ (where ρ is the population's correlation coefficient).The alternative hypothesis H_a: $\rho \neq 0$. The rank coefficient should be between +1 to -1. A +1 value implies there is perfect agreement of two parties, while -1 implies total disagreement of them. Spearman rank-order correlation can be calculated by the following equation (5.10):

$$r_s = 1 - \frac{6\sum {D_i}^2}{n(n^2-1)} \qquad \text{(eq.5.10)}$$

where r_s is the Spearman's rank coefficient between two parties, D_i is the difference between a ranked pair, n is the number rank pairs if all n ranks are in integer.

If tiers are presents in the values, r_s can be found by equation (5.11):

$$r_s = \frac{(n^3 - n) - 6\sum D_i^2 - (T_x+T_y)/2}{\sqrt{(n^3 - n)^2 - (T_x+T_y)(n^3 - n)+T_xT_y}} \qquad \text{(eq.5.11)}$$

where $T_x = \sum_{i=0}^{g}({t_i}^3 - t_i);$ (eq.5.12)

$$T_y = \sum_{i=0}^{g}({t_i}^3 - t_i) \qquad \text{(eq.5.13)}$$

and g is the number of tied groups in variables, t_i is the number of tied values in a tie group. If there is no ties in a variable, T = 0 and it will become equation (5.10).

Table 5.3 displays Spearman rank correlation between groups. Details of ranks of each group were shown in Table 5.4-5.6. Correlation was high (0.654) for academic qualification. Correlations were moderate (0.475-0.591) for gender and job level. Poor correlations were obtained for nature of organization (<0.41). Poor correlations (<0.40) were also obtained for role of employer and work experience, except some rank pairs (between non-freshmen (with more than 5 years' work experience): >0.50; owner vs management company/others: ≥ 0.47; contractors vs others/management company: ≥0.47).

Table 5.3 Summary for comparisons of KPIs' rankings among groups (partially extracted from Ho *et al*., 2021)

No.	Sub-groups in comparison		r_s	*p*-value	Significant relationship
G1: Gender	Male	Female	0.591**	0.008	Yes
G2: Work experience	(≤5 years)	(b) (>5 to <20 years)	0.396	0.093	No
		I (20 to 30 years)	0.350	0.142	No
		(d) (>30 years)	0.120	0.624	No
	(>5 to <20 years)	(c) (20 to 30 years)	0.661**	0.002	Yes
		(d) (>30 years)	0.536**	0.018	Yes
	(20 to 30 years)	(d) (>30 years)	0.505*	0.027	Yes
G3: Nature of organization	Government	Non-government public organization	0.190	0.435	No
		Private	0.112	0.647	No
	NGO	Private	0.406	0.085	No
G4: Role of employer	Owner/developer	Management company	0.859**	0.000	Yes
		Contractors	0.380	0.108	No
		Others	0.470*	0.042	Yes
	Management company	Contractors	0.470*	0.042	Yes
		Others	0.370	0.119	No
	Contractors	Others	0.516*	0.024	Yes
G5: Job level	Strategic level	Tactical level	0.475*	0.040	Yes
G6: Academic qualification	Sub-degree or undergraduate degree	Postgraduate degree	0.654**	0.002	Yes

**correlation is significant at the 0.01 level (2-tailed).
*correlation is significant at the 0.05 level (2-tailed).

In Table 5.3, low level of significant (<0.40) were obtained between freshmen (≤ 5 years' work experience) and non-freshmen (>5 years' work experience), which may be due to lack of practical experience of freshmen in managing retrofit projects. For other non-freshmen groups, moderate to high (0.505-0.661) correlations were obtained. Non-freshmen groups were more emphasized on investment cost ($) but less likely to emphasis target green building level and normalized energy savings (kWh/m^{2}year) as compared to the freshmen.

Another low level of significant (<0.41) were found between different organizations because "the public and private nature of the organization and its facilities influences the preference of performance indicators to a certain degree" (Lavy, 2010). The survey results show that respondents from the private organizations tend to put emphasis on the economic factors (such as payback period and normalized investment cost) and energy/electricity saving, while respondents from the government pay more concerns for users' perspective (such as Δ indoor carbon dioxide levels or harmful substances (ppm), target IAQ class, target workplane illuminance (lux) and target equivalent continuous weighted sound pressure level (dBa)). For respondents from the NGO, they emphasized health and safety issue (ratio of actual to target no. of statutory orders removed), energy savings and user's satisfaction (such as target IAQ class, target working plane illuminance (lux)).

In addition, poor correlation was found for the role of employers The owners and management companies perceived that target IAQ class far more important than the contractors and other groups. As the owners and management companies were the IAQ certificate holders, the certificate can increase business competitiveness by attracting customers who value the commitment of companies to improve environment. In addition, the certificate holders under IAQ Certificate Scheme can further enhance the IAQ at offices by joining the "IAQwi$e" certificate scheme from the Hong Kong Green Organisation Certification, which can gain bonus point(s) or credit when joining other environmental protection award programmes such as BEAM Plus scheme, Green Office Awards Labelling Scheme (GOALS), BOCHK Corporate Environmental Leadership Awards Programme and Caring Company Scheme (Environmental Campaign Committee and Environmental Protection Department, 2021c). For contractors, instead, they paid more emphasis in technical-related KPIs, such as indoor carbon dioxide levels or harmful substances (ppm), energy payback period and target green building label. It may be explained that the green building labelling scheme, for instance, BEAM Plus scheme (Hong Kong), includes not just only energy use, water use, indoor environmental quality, but also other contractors-related aspects, such as site aspect, management, materials and waste aspects, innovations, and additions (Hong Kong Green Building Council, 2020).

Table 5.4 Summary table of mean and ranks for KPIs (G1 and G2)

KPIs (no.)		(G1) Gender				(G2) Work Experience							
		Male		Female		(a) <5 years		5 to < 20 yea		I(c) 20 to < 30 years		(d) ≥30 years	
		Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
1	Energy savings (%)	3.70	2	3.95	1	3.95	2	3.90	=1	3.69	2	3.64	=2
2	Normalized energy savings (kWh/m^{2}year)	3.40	=12	3.65	10	4.00	1	3.48	=12	3.33	11	3.29	16
3	Electricity consumption saving per year (kWh/year)	3.50	4	3.80	=4	3.86	3	3.76	=4	3.54	3	3.33	15
4	Energy payback period (year)	3.38	14	3.60	=11	3.59	=8	3.48	=12	3.36	=9	3.40	=10
5	Target green building label	3.07	19	3.40	=17	3.59	=8	3.33	18	2.97	18	2.95	19
6	Payback period (year)	3.40	=12	3.70	=7	3.68	=6	3.48	=12	3.31	=12	3.50	5
7	Return on Investment (%)	3.30	16	3.55	=13	3.59	=8	3.38	=16	3.18	17	3.40	=10
8	Internal rate of return (%)	3.09	18	3.40	=17	3.45	17	3.19	19	2.87	19	3.24	17
9	Investment cost ($)	3.72	1	3.85	3	3.73	5	3.90	=1	3.74	1	3.69	1
10	Normalized investment cost ($/m^2)	3.46	=6	3.60	=11	3.68	=6	3.52	11	3.49	4	3.36	=12
11	Life Cycle Cost ($)	3.41	11	3.90	2	3.55	=13	3.62	=8	3.38	=6	3.48	=7
12	Increase of building value (%)	3.42	=9	3.50	15	3.36	19	3.62	=8	3.36	=9	3.48	=7
13	Ratio of actual to target no. of statutory orders removed (%)	3.46	=6	3.45	16	3.49	16	3.47	15	3.44	5	3.49	6
14	Ratio of actual to target no. of accidents per year reduced (%)	3.38	14	3.80	=4	3.55	=13	3.81	3	3.31	=12	3.36	=12
15	Target Indoor air temperature (°C)	3.44	8	3.70	9	3.59	=8	3.57	10	3.28	=14	3.62	4
16	Δ Indoor carbon dioxide levels or harmful substances (ppm)	3.52	3	3.75	6	3.55	=13	3.71	6	3.38	=6	3.64	=2
17	Target IAQ class	3.48	5	3.55	=13	3.82	4	3.76	=4	3.28	=14	3.43	9
18	Target workplane illuminance (lux)	3.42	=9	3.70	=7	3.59	=8	3.67	7	3.38	=6	3.36	=12
19	Target equivalent continuous weighted sound pressure level (SPL) (dBA)	3.27	17	3.35	19	3.41	18	3.38	=16	3.21	16	3.21	18

Table 5.5 Summary table of mean and ranks for KPIs (G3 and G4)

KPIs (no.)		(G3) Nature of organization						(G4) Role of current employer							
		(a) Government		(b) Non- gov. pIic		(c) Private		(IOwner		(e)Management company		(f)Contractor		(g)Others	
		Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
1	Energy savings (%)	3.55	=9	3.78	1	3.78	2	3.70	2	3.70	2	3.83	1	3.95	1
2	Normalized energy savings (kWh/m^{2}year)	3.64	=6	3.57	=4	3.41	=12	3.51	=8	3.39	=13	3.33	14	3.63	=3
3	Electricity consumption saving per year (kWh/year)	3.36	=16	3.48	11	3.61	3	3.58	=4	3.52	=6	3.61	=3	3.58	6
4	Energy payback period (year)	3.36	=16	3.57	=4	3.41	=12	3.4	16	3.27	=16	3.61	=3	3.74	2
5	Target green building label	3.45	=12	3.09	18	3.11	19	3.23	=18	3.02	19	3.50	8	2.84	19
6	Payback Period (year)	3.64	=6	3.35	=16	3.48	=5	3.53	=6	3.39	=13	3.44	11	3.53	7
7	Return on Investment (%)	3.45	=12	3.39	15	3.34	16	3.44	=13	3.34	15	3.22	16	3.37	13
8	Internal rate of return (%)	3.36	=16	3	19	3.17	18	3.23	=18	3.16	18	3.11	=18	3.00	18
9	Investment cost ($)	3.64	=6	3.48	11	3.83	1	3.72	1	3.82	1	3.78	2	3.63	=3
10	Normalized investment cost ($/m^2)	3.55	=9	3.48	11	3.48	=5	3.47	=10	3.55	5	3.61	=3	3.26	14
11	Life Cycle Cost ($)	3.73	=4	3.48	11	3.46	10	3.44	15	3.5	=8	3.56	=6	3.47	=8
12	Increase of building value (%)	3.27	19	3.52	=7	3.44	11	3.53	=6	3.5	=8	3.39	=12	3.16	17
13	Ratio of actual to target no. of statutory orders removed (%)	3.47	=9	3.48	11	3.48	=5	3.46	12	3.48	=10	3.49	9	3.46	12
14	Ratio of actual to target no. of accidents per year reduced (%)	3.73	=4	3.52	=7	3.40	15	3.44	=13	3.48	=10	3.39	=12	3.47	=8
15	Target Indoor air temp. (ºC)	3.45	=12	3.61	3	3.48	=5	3.51	=8	3.52	=6	3.28	15	3.63	=3
16	Δ Indoor carbon dioxide levels or harmful substances (ppm)	3.91	1	3.57	=4	3.51	4	3.58	=4	3.57	4	3.56	=6	3.47	=8
17	Target IAQ class	3.82	=2	3.74	2	3.41	=12	3.65	3	3.64	3	3.17	17	3.21	=15
18	Target workplane illuminance (lux)	3.46	=12	3.47	14	3.47	9	3.47	=10	3.48	=10	3.47	10	3.47	=8
19	Target equiv. continuous weighted SPL (dBA)	3.82	=2	3.35	=16	3.19	17	3.37	17	3.27	=16	3.11	=18	3.21	=15

Table 5.6 Summary table of mean and ranks for KPIs (G5 and G6)

KPIs (no.)		(G5) Job Title				(G6) Academic qualification			
		Strategic level		Tactical level		Sub Degree/ Bachelor		Postgraduate degree	
		Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
1	Energy savings (%)	3.82	=2	3.73	1	3.68	=1	3.8	1
2	Normalized energy savings (kWh/m^2year)	3.55	11	3.42	=8	3.35	=14	3.51	6
3	Electricity consumption saving per year (kWh/year)	3.82	=2	3.45	7	3.53	5	3.58	=3
4	Energy payback period (year)	3.61	8	3.36	13	3.38	=14	3.46	=12
5	Target green building label	3.29	18	3.07	19	3.00	19	3.2	18
6	Payback Period (year)	3.74	6	3.35	=14	3.53	5	3.44	15
7	Return on Investment (%)	3.47	15	3.31	16	3.3	16	3.39	16
8	Internal rate of return (%)	3.26	19	3.1	18	3.08	18	3.19	19
9	Investment cost ($)	4.11	1	3.59	2	3.68	=1	3.79	2
10	Normalized investment cost ($\$/m^2$)	3.79	4	3.35	=14	3.35	=14	3.55	5
11	Life Cycle Cost ($)	3.53	=12	3.47	=5	3.45	=10	3.5	=7
12	Increase of building value (%)	3.53	=12	3.41	10	3.38	=12	3.48	=9
13	Ratio of actual to target no. of statutory orders removed (%)	3.49	14	3.46	4	3.47	=8	3.46	=12
14	Ratio of actual to target no. of accidents per year reduced (%)	3.58	=9	3.40	=11	3.45	=10	3.45	14
15	Target Indoor air temperature (^oC)	3.68	7	3.42	=8	3.55	3	3.48	=9
16	Δ Indoor carbon dioxide levels or harmful substances (ppm)	3.58	=9	3.55	3	3.5	7	3.58	=3
17	Target IAQ class	3.76	5	3.40	=11	3.53	5	3.5	=7
18	Target Work plane illuminance (lux)	3.46	16	3.47	=5	3.47	=8	3.47	11
19	Target Equivalent continuous weighted sound pressure level (dBA)	3.37	17	3.23	17	3.25	17	3.29	17

5.3.5 Relative Importance Index (RII)

The relative important index of each KPI was evaluated by the following equation (5.14):

$$RII = (\sum_{r}^{N} I_r)/(I_m \cdot N) \tag{eq.5.14}$$

where I_r is the importance rating (from 1 to 5) given by each respondent to a KPI, I_m is its maximum importance level, and N is the total number of respondents. According to the calculation results, the range of RII varies from 0.20 to 1.00.

5.3.6 Mean score, standard deviation and rankings

Based on all the valid responses, a mean score was calculated for each of the KPIs, and the calculation results in Table 5.7 show that the ratings ranged from 3.14-3.76.

5.4 Finalized KPIs

To shortlist the most important KPIs for pragmatic use in building retrofit performance evaluation, a score of ≥3.45 was used as a cut-off mark for inclusion (Table 5.8). This rating, being the mean between 3.14 and 3.76, represents a moderate-to-high importance level. Thus, a total of 13 KPIs, covering all the four performance aspects, were shortlisted (Table 5.9).

The extraction of the most representative KPIs was based on two criteria: the rank of the KPI and the grouping category. A representative KPI can help to replace the other KPIs to reduce labor cost and workload for recording and processing all the needed performance data. Among the13 KPIs, KPI-1, KPI-2, and KPI-3 can be used to indicate the energy-saving performance of a retrofit project. KPI-1 energy savings (%) (rank: 1) got the highest rank, which implied that the practitioners regarded this KPI to be the most important. It can replace the other two similar KPIs, which only ranked the 12th and the 3rd respectively. Therefore, KPI-1, which can cover the representations of KPI-2 or KPI-3, was taken for use.

For KPI-9, KPI-10 and KPI-11, these KPIs were related to cost evaluation of a retrofit project. Thus, they can be grouped under one category. As KPI-9 (investment cost ($) (rank:2) got higher rank as compared with the other two KPIs [KPI-10 (normalized in-vestment cost ($/m^2) (rank =8), KPI-11 (life cycle cost) (rank: =8)], investment cost was used to represent the others for simplification. Additionally, when compared with KPI-9, KPI-11(life cycle cost) is less feasible in practice. When the buildings have not yet been demolished, a large among of data collection will generate unknown parameters for collectors and distrust the data (Kumar *et al.*, 2013). Cost elements such as operating and maintenance costs, in the long run, could hardly be accurately determined at the time when a retrofit project is implemented (Lai, 2010).

For KPI-16 and KPI-17, they were related to indoor air quality. Despite their similar ranking, (KPI-16: rank: =3 and KPI-17: rank: 5), KPI-17 (Target IAQ class) covered 12 parameters in the assessment and hence more representative than a single parameter in KPI-16 (Δ Indoor carbon dioxide levels or harmful substances (ppm)). The 12 parameters (with 10 chemical parameters) for the indoor air quality assessments include: carbon dioxide (CO_2) and other pollutants, namely carbon monoxide (CO), respirable suspended particulates (PM_{10}), nitrogen dioxide (NO_2), formaldehyde (HCHO), total volatile organic compounds (TVOC), mould, radon and airborne bacteria. It is simple to evaluate the performance of retrofitted buildings by referring to the target IAQ class certificate ("Good Class" or "Excellent Class"), and it is administered by the Environmental Protection Department of the Hong Kong government, is also authoritative (Environmental Campaign Committee and Environmental Protection Department, 2021).

For KPI-15, it was only covered in the assessment of IAQ class for building projects completed before 2019. Thus, it was an independent indicator. Participants ranked KPI-16 (Δ indoor carbon dioxide levels or harmful substances (ppm): rank = 3) over KPI-15 (target indoor air temperature (°C): rank: 6) because the occupants can adjust themselves (e.g., putting on or off their clothes) to suit the indoor thermal comfort condition, while they can hardly notice the concentration of the carbon dioxide or harmful sub-stances, not to mention removing such substances. Participants may, therefore, perceive KPI-16 as more important than KPI-15 for building retrofits.

The rest of the original KPIs, i.e., KPI-6, KPI-13, KPI-14, KPI-15, and KPI-18, are independent indicators without overlaps. Thus, they were retained on the KPIs list.

Table 5.7 Summary table of mean, RII and ranks for KPIs

KPI (no.)		Survey												Focus group			
		Strategic (n=38)				Tactical (n=86)				Overall (n=124)				(n=10)			
		Mean	RII	SD	Rank	Mean	RII	SD	Rank	Mean	RII	SD	Rank	Mean	RII	SD	Rank
1	Energy savings (%)	3.82	0.76	0.77	=3	3.73	0.75	0.89	1	3.76	0.75	0.86	1	4.4	0.88	0.66	=9
2	Normalized energy savings (kWh/m^{2}year)	3.55	0.71	0.75	11	3.42	0.68	0.91	=9	3.46	0.69	0.87	=12	4	0.8	1.00	=19
3	Electricity consumption saving per year (kWh/year)	3.82	0.76	0.78	=3	3.45	0.69	1.05	7	3.56	0.71	0.98	=3	4.4	0.88	0.66	=9
4	Energy payback period (year)	3.61	0.72	0.93	8	3.36	0.67	0.96	13	3.44	0.69	0.95	=15	4.6	0.92	0.66	6
5	Target green building label	3.29	0.66	1	18	3.07	0.61	1.09	19	3.14	0.63	1.07	19	4.7	0.94	0.46	=3
6	Payback Period (year)	3.74	0.75	1.07	6	3.35	0.67	1.02	=15	3.47	0.69	1.04	=10	4.8	0.96	0.40	2
7	Return on Investment (%)	3.47	0.70	1.12	16	3.31	0.66	0.96	16	3.36	0.67	1.01	16	4.1	0.82	0.83	=17
8	Internal rate of return (%)	3.26	0.65	0.96	19	3.10	0.62	0.9	18	3.15	0.63	0.92	18	4.2	0.84	0.6	=14
9	Investment cost ($)	4.11	0.82	0.78	1	3.59	0.72	0.86	2	3.75	0.75	0.84	2	4.7	0.94	0.46	=3
10	Normalized investment cost ($/m^2)	3.79	0.76	0.92	4	3.35	0.67	0.83	=15	3.48	0.70	0.87	=8	4.2	0.84	0.6	=14
11	Life Cycle Cost ($)	3.53	0.71	0.89	=13	3.47	0.69	0.84	5	3.48	0.70	0.87	=8	4.7	0.94	0.46	=3
12	Increase of building value (%)	3.53	0.71	1.04	=13	3.41	0.68	0.87	10	3.44	0.69	0.93	=15	4.3	0.86	0.78	=11
13	Ratio of actual to target no. of statutory orders removed (%)	3.49	0.70	0.93	14	3.46	0.69	0.95	6	3.46	0.69	0.95	=12	5	1.00	0.00	1
14	Ratio of actual to target no. of accidents per year reduced (%)	3.58	0.72	1.05	=10	3.40	0.68	0.9	=12	3.45	0.69	0.95	13	4.1	0.82	0.94	=17
15	Target Indoor air temperature (ºC)	3.68	0.74	0.89	7	3.42	0.68	0.9	=9	3.50	0.70	0.9	6	4	0.80	1.10	=19
16	Δ Indoor carbon dioxide levels or harmful substances (ppm)	3.58	0.72	0.94	=10	3.55	0.71	0.84	3	3.56	0.71	0.87	=3	4.2	0.84	0.98	=14
17	Target IAQ class	3.76	0.75	0.98	5	3.40	0.68	0.93	=12	3.51	0.70	0.96	5	4.5	0.90	0.50	7
18	Target workplane illuminance (lux)	3.46	0.70	0.81	15	3.47	0.69	0.80	4	3.47	0.69	0.8	=10	4.2	0.84	0.60	=14
19	Target equivalent continuous weighted sound pressure level (dBA)	3.37	0.67	0.92	17	3.23	0.65	0.75	17	3.27	0.65	0.83	17	4.3	0.86	0.64	=11

Where Blue highlight represents the shortlisted KPIs. (Green: Environmental aspect; Light Red: Economic aspect; Grey: Health and Safety aspect; Yellow: Users' Perspective)

Table 5.8 Range of KPIs score

Score	Inclusion of aspects	No. of KPIs included
≥3.00 (Moderate)	4	19
≥3.40	4	15
≥3.45 (Moderate to High)	4	13
≥3.50	3	6
≥4 (High)	0	0

Table 5.9 Finalized KPIs

Original (13 KPIs)	Remark	New (8 KPIs)
KPI-1: Energy savings (%) KPI-2: Normalized energy savings (kWh/m^{2}year) KPI-3: Electricity consumption saving per year (kWh/year)	KPI-2, 3 is combined with KPI-1. Reason: They all measured the amount of energy saving with various units. Hence, use KPI-1 as it had the highest rank (rank 1 as compare with rank =4 and 12)	KPI-1*: Energy savings (%)
KPI-6: Payback Period (year)	-	KPI-2*: Payback Period (year)
KPI-9: Investment cost ($) KPI-10: Normalized investment cost ($/m^2) KPI-11: Life Cycle Cost ($)	KPI-9 is combined with KPI-10 and 11 with similar meaning. Hence, use KPI-9 with a higher rank (rank 2 vs rank =8). For KPI-11, it is difficult to find out all the costs throughout its life cycle.	KPI-3*: Investment cost ($)
KPI-13: Ratio of actual to target no. of statutory orders removed (%)	-	KPI-4*: Ratio of actual to target no. of statutory orders removed (%)
KPI-14: Ratio of actual to target no. of accidents per year reduced (%)	-	KPI-5*: Ratio of actual to target no. of accidents per year reduced (%)
KPI-15: Target Indoor air temperature (°C)	-	KPI-6*: Target Indoor air temperature (°C)
KPI-16: Δ Indoor carbon dioxide levels or harmful substances (ppm) KPI-17: Target IAQ class	Although KPI-16:(rank =3) is slightly higher than KPI-17:(rank 5), KPI-17 is more comprehensive, which covers 12 IAQ parameters in the assessment (The Government of the Hong Kong Special Administrative Region, 2019).	KPI-7*: Target IAQ class
KPI-18: Target Work plane illuminance (lux)	-	KPI-8*: Target Work plane illuminance (lux)

After the foregoing activities (literature review, focus group, and survey), the shortlisted KPIs, belonging to four different aspects, were consolidated and presented in a three-level hierarchical in Figure 5.1.

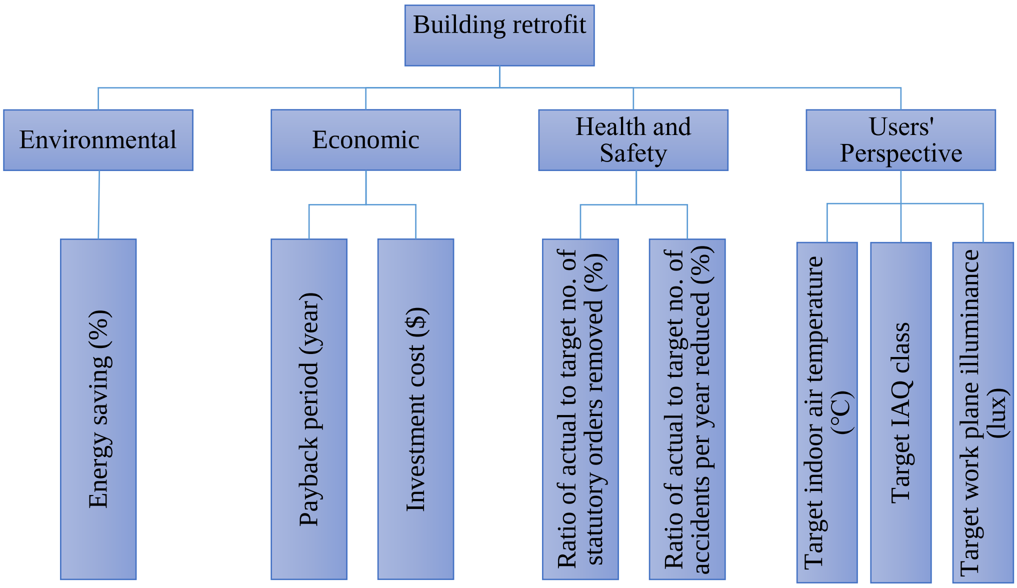


Figure 5.1 Top eight KPIs for building retrofit uation

5.5 Discussion and comments from respondents

<u>Practical barriers of building energy retrofits in Hong Kong</u>

The online survey provided significant implication to the building retrofit practice for energy efficiency in Hong Kong. From the survey, aside from the comments provided to the 19 KPIs, the participants were engaged in elaborating the building retrofit projects based on their practice in Hong Kong. Part 3 of the survey was an open-ended question, and the participants were asked to provide any comments.

Two types of barriers of building energy retrofits were identified based on the findings from the survey, namely i) high evaluation cost and difficulty of getting precise estimation and ii) variation in project nature.

i) High evaluation cost and the difficulty of getting precise estimation

The core information to support building retrofitting performance assessment are related to safety and properly working of the assets, health and comfort, space functionality and energy. These information are usually obtained by FM managers who carry out corrective maintenance and conduct technical inspections and by users who report complaints and fill-in satisfaction questionnaires, which were designed to help to improve performance during operational phase of a building (Bortolini and Forcada, 2018). Thus, systematically collect all necessary data to support building retrofitting performance evaluation is very costly. One of the survey respondents mentioned in the survey that

"*…initial cost (for evaluating the building retrofit performance) can be high…*"

Though data acquisition can be relatively simple and cheap using modern and powerful hardware systems and software Kumar et al. (2013), data overload can be a problem which involves sophisticated data mining algorithm to obtain useful information (Charnes et al., 1984). Thus, whether it is worth the effort and cost to collect the data for performance evaluation is a common decision-to-make encountered by FM managers (Kumar et al., 2013). If all the KPIs identified from the literature review are used to evaluate the performance of building retrofits, considerable efforts and resources will be needed to obtain and process the data. Kumar et al. (2013)'s study stated that having a lot of indicators was impractical and indicators should be simple to allow the possibility of benchmarking. Moreover, it is difficult to collect the accurate energy consumption data in commercial buildings in Hong Kong. A survey respondent who worked from a private management company stated:

"It (building retrofits) cannot give the precise percentage as the change of the weather might cause the energy consumption to increase significantly. For the energy saving aspect we do keep at 2% per year depending on electricity side only."

In Hong Kong, where there are a lot of chilled water pipes and air ductworks in the air-condition system, sub-meters are not commonly installed to monitor the energy consumption of different parts of building services systems. Without sub-metering of a chiller plant, it is difficult to measure the actual energy saving resultant from the implementation of retrofit works. The additional cost of sub-meter for chiller plant is usually high as extra work is needed to modify the relevant circuits of the existing system (Lai *et al*., 2008). This has been proved in Ho *et al*. (2021)'s study, whose results show that, despite the high ranking and mean importance score of the indicator: "annual energy cost savings ($/year)", it was not selected as the KPIs for evaluating the performance of commercial building retrofit due to the same reason: "no record data, too costly to work out and not usually used." as raised by the experienced FM practitioners.

ii) Variation in project nature

It is common to upgrade the existing equipment at the end of the equipment life or when it comes to failure. Traditional retrofits practice focuses on replacing single piece of equipment, such as chillers, lighting, instead of the overall building performance, system optimization or controls integration (Amann and Mendelsohn, 2005). Also, physical conditions of the equipment are more emphasized than the budgeting. The intention to extend the life span of the equipment or systems can regarded to be the most crucial reason in some retrofitting projects and the budget planning is the second concern for project execution. These have been revealed by some survey respondents:

"Many retrofit projects initiation was based on the order of equipment or system end of life, no spare part support, change of use/demand, justifiable energy saving whereas functional or environmental enhancement are usually in the lowest priority.".

"…equipment life span may somehow should be more crucial for budgeting and project execution."

The following statements from the survey respondents further indicated that the applicability of the KPIs in the evaluation tool may vary depending on the nature and scope of the retrofitting projects. In practice, building professionals have their own classification on building retrofitting projects. Some of them regarded the identified KPIs are not applicable to the decision of certain types of building retrofitting projects as different stakeholders may hold different opinions. The building retrofitting practice continues to develop, and thus existing literature may not fully reflect the practical KPIs used by practitioners.

"The above answers (for KPIs) were generic, in fact the scores should be depending on the nature of the retrofitting project."

"Some KPIs may not be commonly used or considered by management, and some may not be applicable when designing the retrofitting project, while some may be irrelevant to the reason for carrying out retrofit."

"Special attention should be taken in case of the retrofit project carrying out phase by phase as the newly added and the existing system may be connected and worked together at the same time. Final commissioning of the whole system is necessary at the final stage of the project.".

From a managerial perspective, the building performance indicators depends on the resources (e.g. financial, technological and labor) that are available and the quality of service that should be achieved (Preiser and Nasar, 2008). According to Cable and Davis (2004) and Cripps (1998), facilities must be assessed with an organization's goals and mission to evaluate how well a facility helps the organization meet its goals and fulfil its mission. In some retrofit projects such as shopping arcade, renovation may not take place to minimize disruption of business operation. For example, the average cost of disruption relative to the initial capital cost can be up to 12%, where the cost of revocability relative to the initial capital cost can be up to 119% over a 60-year life from two office retrofit projects in UK (Tokede and Ahiaga-Dagbui, 2016).

5.6 Summary

In conclusion, the questionnaire survey results provided important information on selecting suitable performance indicators for commercial building retrofits. A total of 124 engineers and directors participated in the survey and 94 of them were having experience in managing office building projects Regarding the indicators' ranking, practitioners with different natures of organization, roles of employer and work experiences had different emphases. From the results in U-test or H-test, female considered life cycle cost more important than male; FM practitioners from tactical level perceived that three of the users' perspective KPIs (related to IAQ, lighting level and noise level) more important than strategic level; respondents with less work experience considered the normalized energy savings (kWh/m^{2}year) more important than the veteran. The questionnaire survey also showed that high evaluation cost, difficulty of getting precise estimation and variation of the project nature were the main difficulties for evaluating the building retrofit performance.

Finally, eight KPIs were shortlisted from the survey, which are: energy savings (%), payback period (year), investment cost ($), ratio of actual to target number of statutory orders removed (%), ratio of actual to target number of accidents reduced (%), target indoor air temperature (^{o}C), target IAQ class, and target workplane illuminance (lux). The feasibility of these KPIs have not been fully tested in real project. Therefore, a series of in-depth interview will be conducted and presented in the next few chapters to find out their importance weights and validate the applicability of these indicators in real projects.

Chapter 6 Model development for assessing commercial building retrofit performance

6.1 Introduction

To develop a sound analytic method for assessing the building retrofit performance in commercial buildings, it is crucial to find out the relative importance weights of the shortlisted KPIs. After crystallizing the KPIs from focus group study and surveys in previous stages, an analytic network process (ANP) model was developed by the Super Decision software. In-depth interviews were then conducted with FM professionals who managed commercial buildings in Hong Kong to find out the importance weights of the KPIs. The theory of ANP was briefly introduced in Chapter 3. This chapter presents the formation of an ANP network, calculation procedure for relative importance weights of KPIs and the findings drawn from the ANP analyses.

6.2 Background for the interviews

As discussed in Chapter 3, in-depth interviews were used for stage 4: method development and validation. As the aim of this research is to develop and validate the analytic method for assessing retrofit performance in commercial buildings, interview method is particularly useful to collect data regarding to case-study buildings.

The goals of the interviews were to (i) identify the relative importance weights of the KPIs, (ii) collect the commercial building retrofit performance data from FM practitioners, and (iii) evaluate the overall building retrofit performance by FM experts. Interview results were used to validate the applicability of the assessment method, which aimed at reflecting the performance of commercial building retrofits from FM perspective.

Comprising three directors (e.g. directorate grade), eight managers and one consultant, they were experienced (7 to over 30 years) in facility management and majority of them were veteran (>80% with over 20 years work experience in facility management and all got a master's degree). Eight of interviewees were from private companies and the others from non-government organization.

They all were professional members in different organizations (ten interviewees were professional members of the Building Services Operation and Maintenance Executives Society (BSOMES) and the Hong Kong Institution of Engineers (HKIE) – the former one is the leading professional institution in Hong Kong specialized in operation and maintenance (O&M) works for buildings and latter one is professional institution in Hong Kong specialized in building services. Eight of them were professional members of the Chartered Institution of Building Services Engineers (CIBSE) and one of them was member of the Hong Kong Institute of Facility Management (HKIFM)).

As all participants had FM work experience in Hong Kong in handling the commercial buildings, they could provide valuable judgement in rating the KPIs and make suggestion to the retrofit assessment tool. Table 6.1 shows the demography of the interviewees.

Table 6.1 Demography of the interviewees

Characteristic	Subgroup	Number	Percentage
Job title	Directorate grade (e.g. chief engineer)	3	25.0%
	Tactical grade (e.g. engineers)	8	66.7%
	Consultant	1	8.3%
Work experience in FM/O&M of buildings (years)	<10	1	8.3%
	10-19	1	8.3%
	20-30	7	58.3%
	>30	3	25.0%
Employer	Non-government public organization	4	33.3%
	Private company	8	66.7%
Buildings/premises that have worked on	Office	11	91.7%
	Retail	9	75%
	Hotel	4	33.3%
	Others	3	25.0%
Professional member (Corporate class or above)	BSOMES	10	83.3%
	CIBSE	8	66.7%
	HKIE	10	83.3%
	HKIFM	1	8.3%
	Others (such as CIPHE, HKICBIM, IFMa, ASHRAE, CEng, RPE, Energy Assessor)	5	41.6%
Highest academic qualification	Associate degree/diploma/certificate	-	-
	Bachelor degree	-	-
	Master degree	12	100%
	Doctorate degree	-	-

6.2.1 Evaluation form for the interviews

Prior to the conduction of the interviews, questionnaires and a four-minute online introduction video (Appendix C) were sent to the participants to allow them to get more familiar with the research study. In total, twelve interviews were conducted, of which 11 were conducted online and one in person. The questionnaire (Appendix D) consisted of three parts.

Part 1 asked the interviewees to provide information of a evaluated commercial, including the name (optional), types of premises in the building, building's age, number of storeys in the building, total gross floor area, internal floor area, project duration, adopted retrofit measures, cost of measures, project costs and other additional information for the project. Part 2A asked the interviewees to provide personal information, including work experiences in the building industry, nature of employer, types of building or premises that they are involved in managing, professional membership, and academic qualification. Part 2B required the interviewees to rate the importance weights of KPIs. It contained the network diagram of the KPIs and a series of pairwise comparison tables with 9-point scale (*"1" = "Equal importance", "3"= "Moderate importance", "5"= Strong importance, "7" = "Very strong importance", "9= Absolute importance", "2, 4, 6, 8" = intermediate value*). Part 3 (self-completed after the interview), the interviewees were invited to evaluate the retrofit performance by providing actual data of the eight KPIs (if applicable to the project, e.g. achieved value, target value or the difference before and after retrofit) and indicate their performance scores on a five-point Likert scale (*1 = Very poor; 2 = Poor; 3 = Fair; 4 = Good; 5 = Very good*) with supporting reasons, data, and other information.

The interviews lasted 35 minutes on average. The relative importance rating of KPIs were identified through performing pairwise comparison by the interviewees using SuperDecision Software. After the interviews, interviewees were asked to complete Part 3 of the questionnaire. The interview process is illustrated in Figure 6.1.

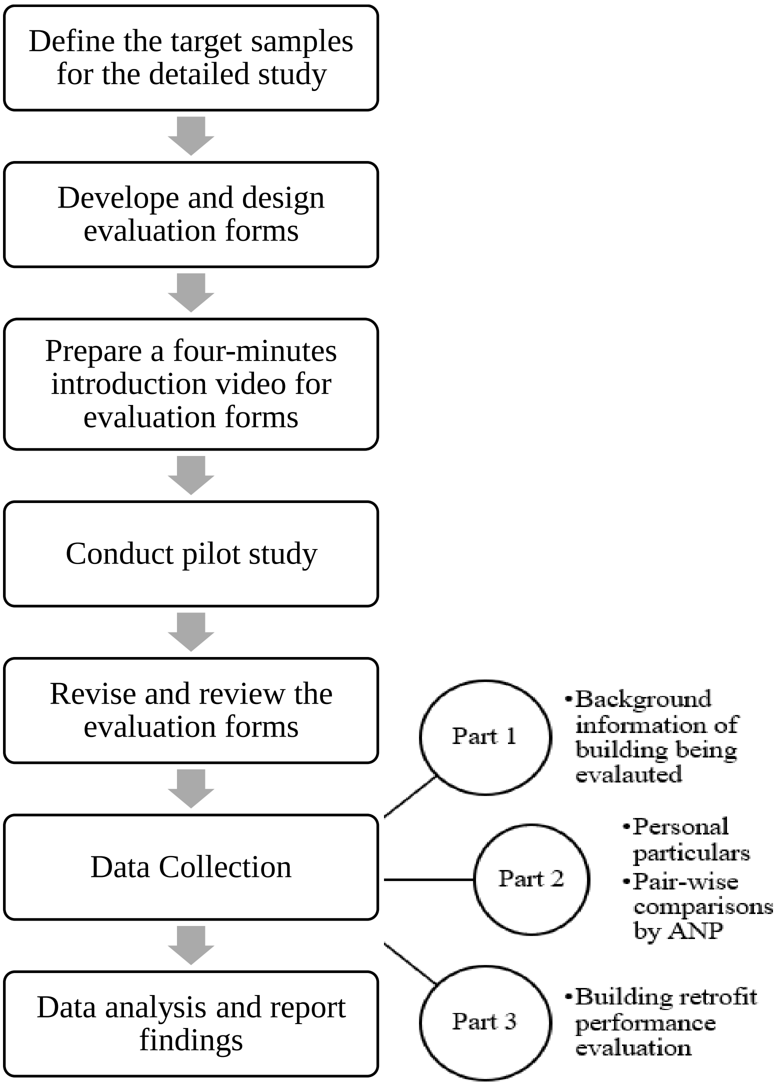


Figure 6.1 Questionnaires design for interviews

6.3 Four steps to solicit the importance weights of KPIs

Four main steps of ANP are included: i) construction of ANP network, ii) pairwise comparisons and local priority vectors, iii) supermatrix formation and iv) final priorities and selection (Saaty, 1996). The proposed ANP algorithm procedure was established based on the concept developed by Saaty (1996) and extend as represented step-by-step in Figure 6.2.

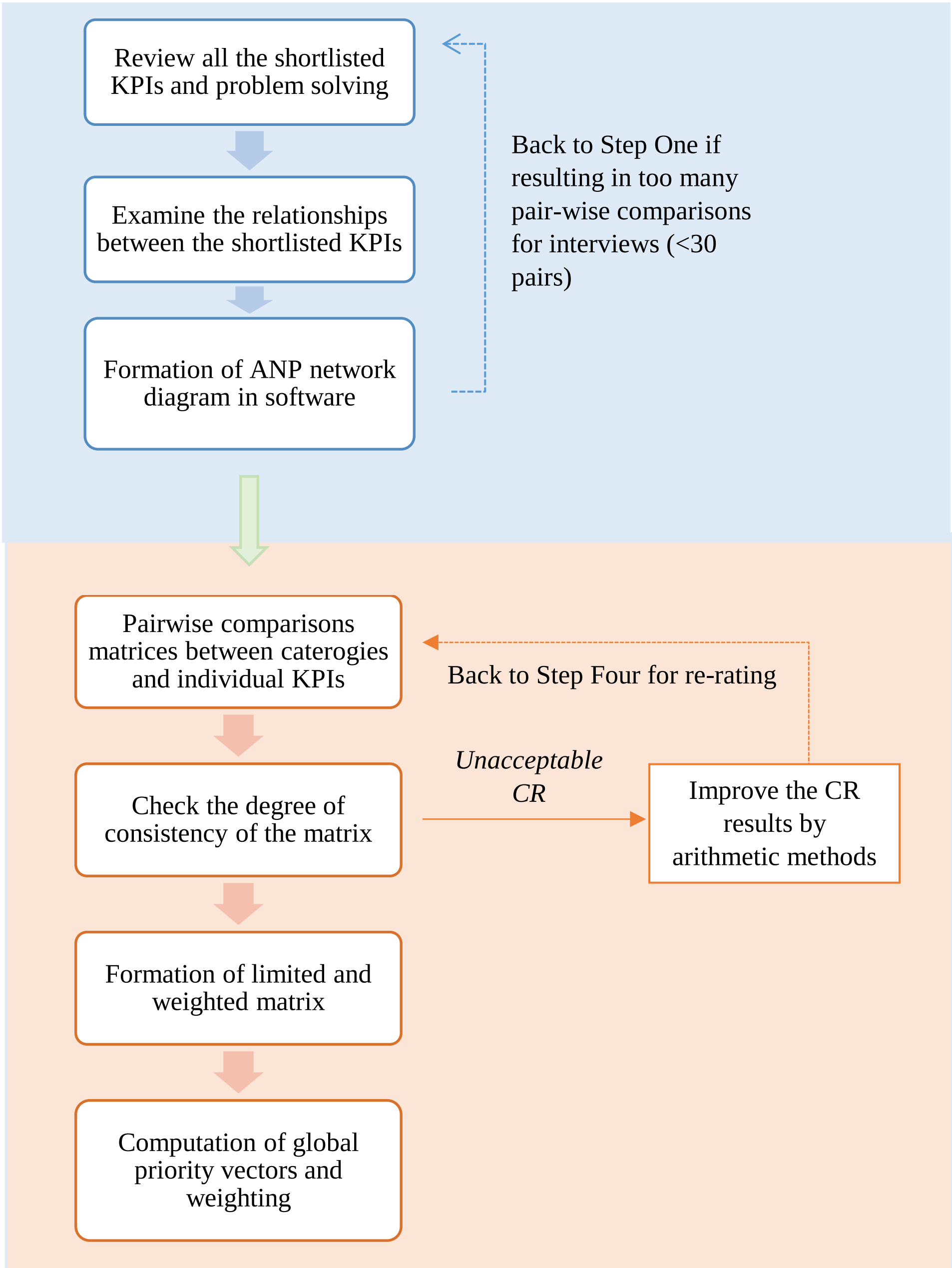


Figure 6.2 The ANP approach for prioritizing key performance indicators

The first part of ANP formation involved reviewing the shortlisted KPIs and examine their inter-relationships with research experience groups. If too many pair-wise comparisons were resulted (>30) from the KPIs, it can be too time-consuming for interviewees to answer and rate the score and need to be revised the total number of

KPIs included in the interview. After forming the ANP network, pair-wise comparisons were made between categories and individual KPIs in Step 4. After that, the degree of consistency in matrix were checked whether it was within a range or acceptable ratio. The consistency ratio was then improved and within the acceptable limit by re-rating the scores of that matrix by the interviewees. The limited and weighted matrix were then calculated in Step 6. The global priority vectors and weighting were also computed in Step 7 to determine the importance weights of the KPIs for evaluation of retrofit performance in commercial buildings.

6.3.1 Construction of ANP network (Step 1)

There were total eight KPIs in four aspects. One KPI for the environmental aspect (energy saving), two KPIs for the economic (payback period (year) and investment cost ($), two KPIs for the health and safety aspect (ratio of actual to target number of statutory orders removed and ratio of actual to target number of accidents per year reduced) and three KPIs for users' perspective (target room air temperature (^{o}C), target IAQ class and target workplane illuminance(lux)) (Figure 6.3 and 6.4). The only difference between Figure 6.3 and Figure 6.4 were the inner dependence of the element/nodes within the users' perspective. More details concerning about the relationship of KPIs are explained at p. 198. The top layer of the network represents the main goal of the decision problem ("categories": includes all the four main aspects in evaluating performance in building retrofit), and the lower levels are the criteria (individual aspect) and sub-criteria levels (KPIs) which can be referred to clusters and nodes respectively. The criteria are evaluated their relative importance to the goal, while the sub-criteria are evaluated for how they are preferred with respect to another criterion.

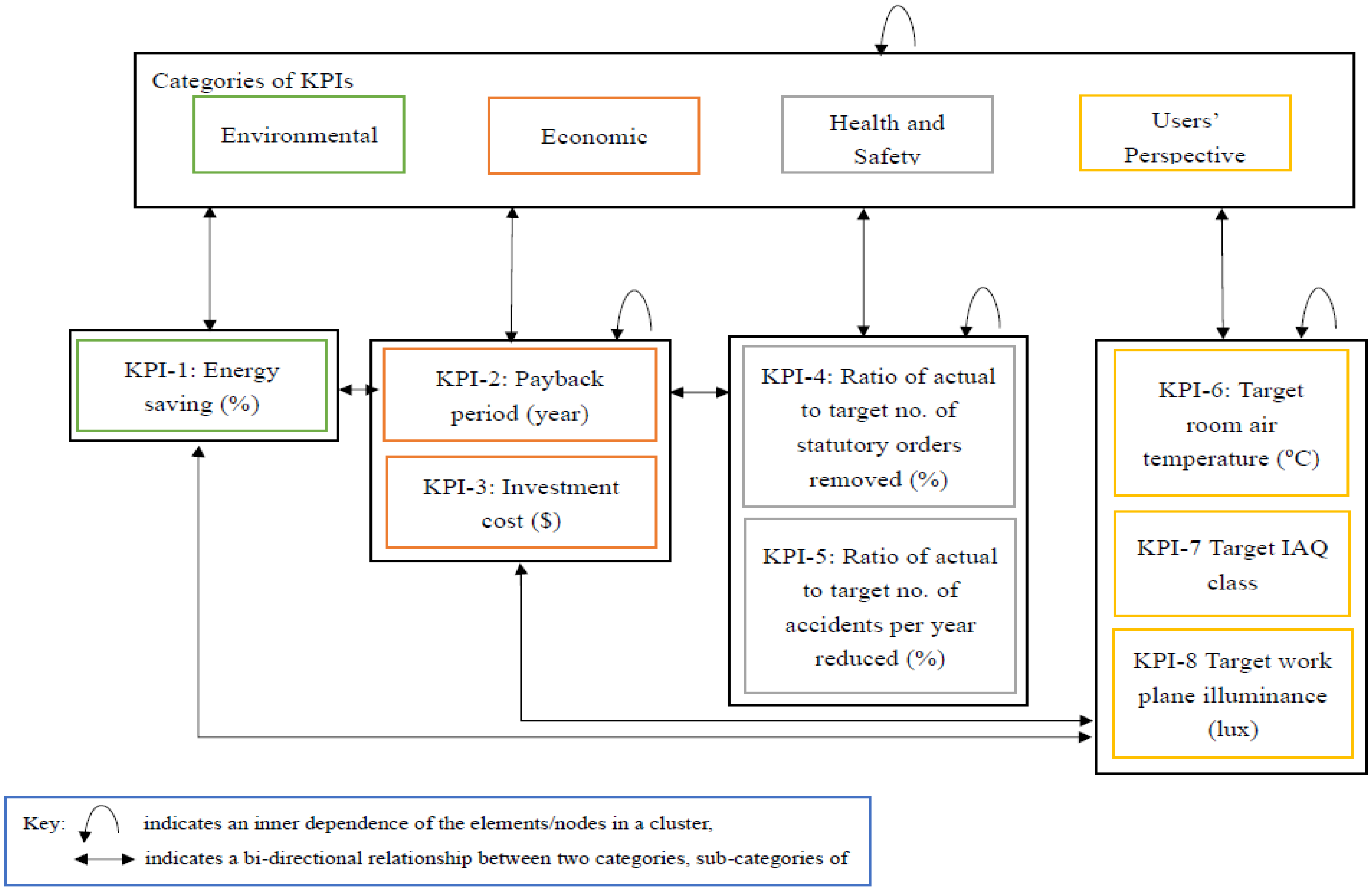


Figure 6.3 Overall ANP network diagram (for retrofitted building before 2019)

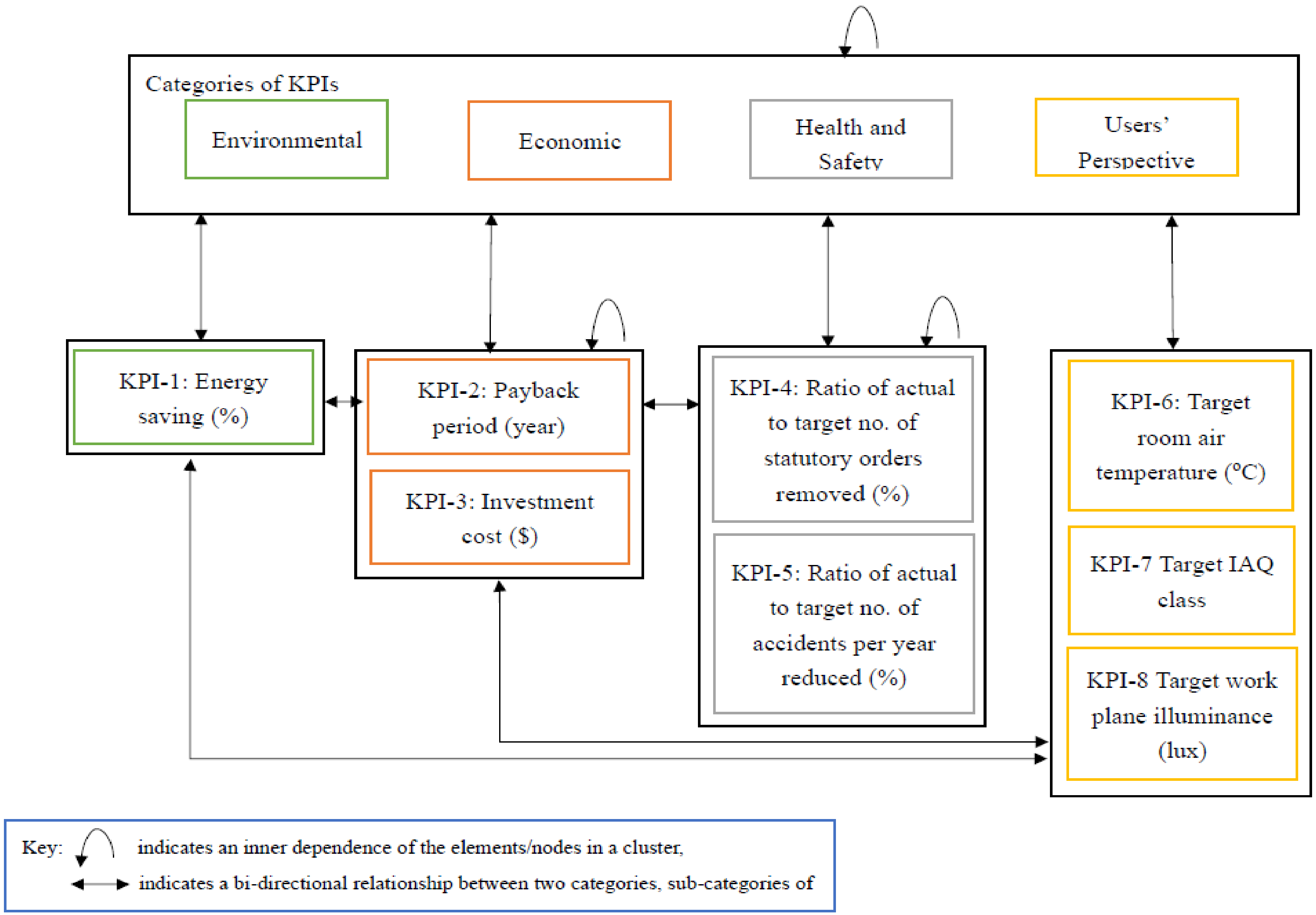


Figure 6.4 Overall ANP network diagram (for retrofitted building after 2019)

Rationale of the inter-relationship between indicators

There are eight KPIs in four aspects, including "environmental", "economic", "health and safety aspect", and "users' perspective". Their inter-relationship is described as follows:

Environmental aspect

Larger amount of energy saved (KPI-1) from implementing the retrofit will lead to a shorter payback period, and hence it can affect the payback period (year) (KPI-2).

Economic aspect

If the payback period (year) (KPI-2) is too long, the design criteria may be adjusted accordingly to reduce the relevant cost. Hence, it can affect the design criteria such as target room air temperature (^{o}C) (KPI-6), target IAQ class (KPI-7), target workplane illuminance (KPI-8), and hence affect the investment cost ($) (KPI-3). On the other hand, the retrofit cost contributes the major amount of the investment cost ($) (KPI-3) and hence it will be used to represent the investment cost for simplification in a case study. The investment cost can affect all the KPI-1 to KPI-8, as higher the retrofit cost, more energy can be saved (KPI-1) from the building by advanced equipment, better functionality (KPI-4 and KPI-5), better the indoor environment (KPI 6 – KPI8), whereas the payback (KPI-2) may be longer or shorter, depends on the technology or equipment used.

Health and safety aspect

Common building defects includes spalling concrete, defective sprinkler system, water seepage and drainage nuisance (Buildings Department, 2002), removal of nuisance notice on Legionnaire's' Disease (Electrical and Mechanical Services Department, 2019) etc. The two indicators, ratio of actual to target number of statutory orders removed (%) and ratio of actual to target no. of accident per year reduced (%) (KPI-4 and KPI-5) can be inter-corelated and help to ensure proper operation and maintenance of building facilities with complying with relevant health, safety, and legal requirements.

Users' perspective

The target room air temperature (^{o}C) (KPI-6) setpoint will affect the amount of electricity usage (KPI-1). With a lower target indoor air temperature, it will affect the investment cost ($) (KPI-3) and payback period (KPI-2). In addition, target room air temperature is one of the parameter in the assessment for the award of the IAQ class (KPI-7) for the retrofit project that completed before 2019 (Environmental Protection Department, 2017), and hence target room air temperature (^{o}C) (KPI-6) and target IAQ class (KPI-7) were inter co-related in assessing the IAQ class for the project completed before 2019. Similarly, both the target IAQ class (KPI-7) and target workplane illuminance (lux) (KPI-8) can affect energy saving (KPI-1), payback period (year) (KPI-2) and investment cost ($) (KPI-3). With a higher requirement on IAQ class (i.e. excellent class), more energy (KPI-1) may be needed to increase air flow rate to remove the pollutants. The advanced technology can affect the investment cost ($) (KPI-3) (depends on the efficiency of equipment) and payback period (years) (KPI-2). For target workplane illuminance (lux) (KPI-8), lighting levels on workplane are co-related to the lighting power density (KPI-1) and use of advanced equipment (investment cost, KPI-3), which can affect the payback period (year) (KPI-2) as well. Table 6.2 presents the inter-relationship between KPIs when constructing the ANP network.

Table 6.2 Relationship matrix of KPIs

Aspect	Relationship Matrix	KPI-1	KPI-2	KPI-3	KPI-4	KPI-5	KPI-6	KPI-7	KPI-8
Enviro.	KPI-1 Energy savings (%)	-	⤴	↵			↵	↵	↵
Econ.	KPI-2 Payback period (year)		-	⤴↵			⤴	⤴	⤴
	KPI-3 Investment cost ($)	⤴	⤴	-	⤴↵	⤴↵	⤴↵	⤴↵	⤴↵
Health & Safety	KPI-4 Ratio of actual to target no. of statutory orders removed (%)			↵	-	⤴↵			
	KPI-5 Ratio of actual to target no. of accident per year reduced (%)			↵	⤴↵	-			
Users' Persp.	KPI-6 Target room air temperature (°C)	⤴	⤴↵	⤴↵			-	^(⤴↵)	
	KPI-7 Target IAQ class	⤴	⤴↵	⤴↵			^(⤴↵)	-	
	KPI-8 Target workplane illuminance (lux)	⤴	⤴↵	⤴↵					-

Note: ⤴ denotes the relationship between two KPIs, for example, KPI at the left will affect the KPI on top.
↵ denotes the relationship between two KPIs, for example, KPI on top will affect the KPI at the left.
'-' represents 'no comparison can be made for the same KPI'.
^ represents it is no longer applicable for retrofit projects that completed after 2019.

6.3.2 Pairwise comparisons and local priority vectors (Step 2)

After constructing the ANP networks based on the inter-relationship between KPIs, the list of pairwise comparisons were formulated from the SuperDecision software. It comprises 13 comparison matrices, with a total of 27 pairwise comparisons (Table 6.3, Appendix E). The FM professionals were asked to provide judgments based on a ratio scale of 1 to 9 as developed by Saaty (2005) as introduced in Chapter 3. They were asked to compare two elements with respect to a control criterion, and thus the result reflects the dominance between elements (where *"1" = "Equal importance", "3"= "Moderate importance", "5"= Strong importance, "7" = "Very strong importance", "9= Absolute importance", "2, 4, 6, 8" = intermediate value*) (Figure 6.5).

Table 6.3 List of pairwise comparisons

Comparisons with respect to “Environmental” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Health and Safety	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Economic” node in “Categories” cluster		
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Health and Safety	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Health and Safety” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environmental
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Users’ Perspective” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environmental
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety

Comparisons with respect to “Economic” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster		
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)

Comparisons with respect to “Users’ Perspective” node in “Categories” cluster		
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)

Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster		
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)
Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster		
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster		
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
Comparisons with respect to “Target indoor air temperature (ºC)” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)
Comparisons with respect to “Target IAQ class” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)
Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

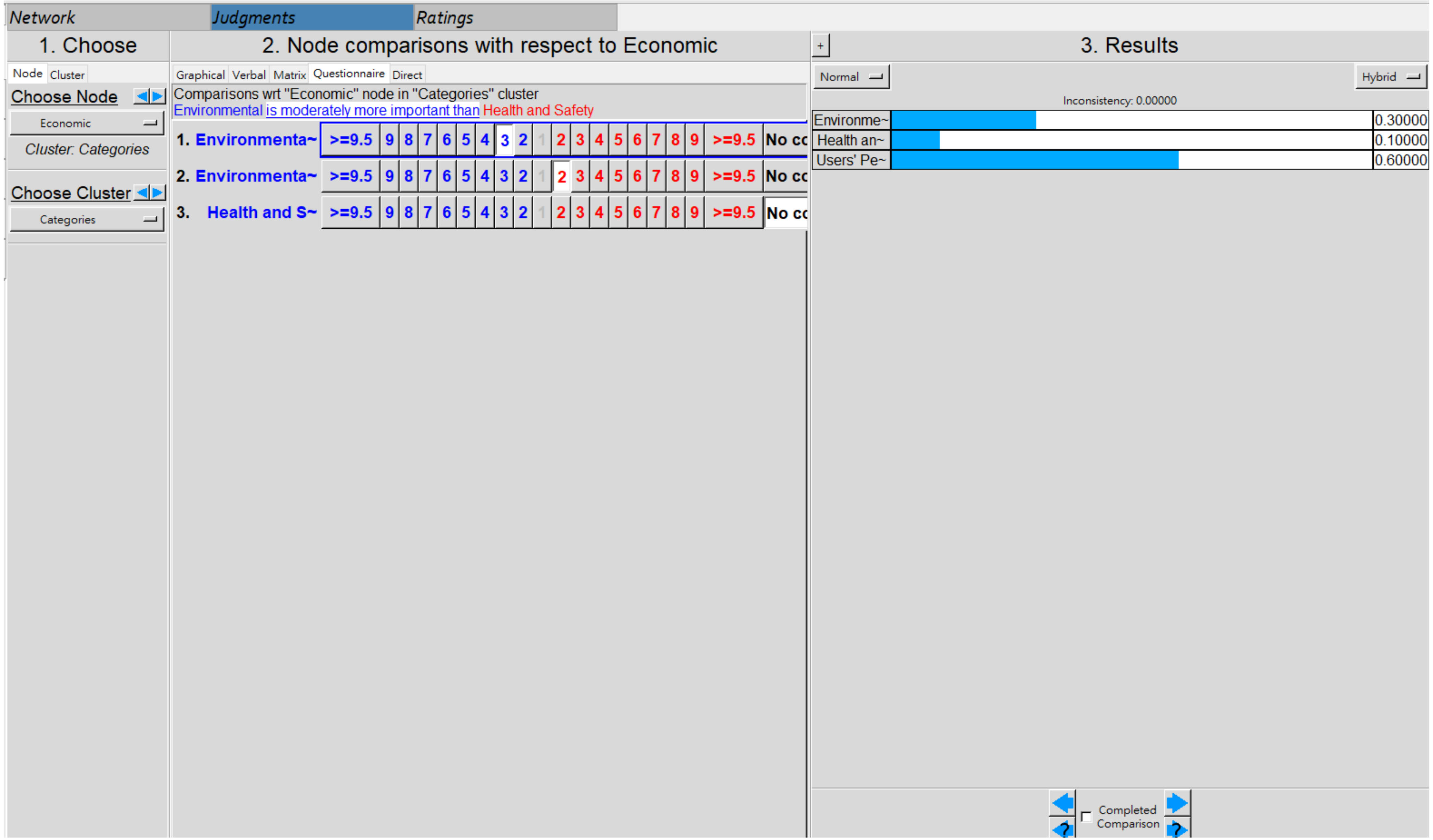


Figure 6.5 Snapshot of the pairwise rating from the SuperDecision software

The first pilot test of interview was conducted in June 2020 and tables for comparison were sent to the participants before the interview. This allowed the participants to preview and get familiar with the contents before the meeting. With a total of 12 interviews, there were more than 300 pairwise comparison.

Local priority vectors

The priority weights of each criterion and the relative importance of the elements can be solved by the SuperDesicion software to compute the following equation:

$$A*\mathrm{w} = \lambda_{\max}*\mathrm{w} \qquad \text{(eq.6.1)}$$

where A represents the matrix of pairwise comparisons; w represents the eigenvector, and λ_{max} represents the largest eigenvalue of A. For a consistency matrix A, the eigenvector can be found from equation (6.2):

$$(\mathrm{A}-\lambda_{\max}\mathrm{I})X=0 \qquad \text{(eq.6.2)}$$

In this study, it only appears 2-by-2 matrix and 3-by-3 matrix. A positive reciprocal matrix A has $\lambda_{max} \geq n$, with equality if and only if A is consistent. Every 2-by-2 matrix positive reciprocal matrix is consistent as $\lambda_{max} = 2$:

$$\begin{bmatrix} 1 & \alpha \\ \alpha^{-1} & 1 \end{bmatrix} \begin{bmatrix} 1+\alpha \\ (1+\alpha)\alpha^{-1} \end{bmatrix} = 2 \begin{bmatrix} 1+\alpha \\ (1+\alpha)\alpha^{-1} \end{bmatrix} \qquad \text{(eq.6.3)}$$

However, not every 3-by-3 positive reciprocal matrix is consistent, but here is fortunate to have again explicit formulas for the principal eigenvalue and eigenvector.

For A = $\begin{bmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{bmatrix}$ (eq.6.4)

where we have $\lambda_{max} = 1+d+d^{-1}$ $d = (ac/b)^{1/3}$ (eq.6.5)

$w_1 = bd/ (1+bd+c/d)$ (eq.6.6)

$w_2 = c/d/ (1+bd+c/d)$ (eq.6.7)

$w_3 = 1/ (1+bd+c/d)$ (eq.6.8)

where $\lambda_{max} = 3$ when d = 1 or c = b/a which is true if and only if *A* is consistent.

Consistency ratio

Consistency is essential in human thinking and validate it in a scientific way. To access the reliability of the experts' judgment, the most widely adopted consistency index is the consistency ratio (CR) (Saaty, 2004b) in equation (6.9):

C.I. (μ) == (λ_{max} – n)/(n-1) (eq.6.9)

where the consistency index (C.I.) reflecting the consistency of participants' judgement and n is the order of matrix *A*. For the average random index (R.I), it can be found based on the matrix size as shown in Table 6.4 (Saaty, 2004b):

Table 6.4 The average random index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	152	1.40	1.45	1.49

where n is the order of matrix

The Consistent Ratio can be found where:

CR =C.I./R.I. (eq.6.10)

If CR=0, then the pairwise comparison matrix is consistent, or otherwise it is not. In general, the value of CR with the consistency threshold is set at CR = 0.1. This means that larger than 10% of the total concern would disrupt consistent measurement. If CR<0.1, the found priority vector is acceptable (Saaty, 2004b).

For 3-by-3 matrix, CR is recommended not larger than 0.05 (Saaty, 2005). In those large-size matrices, the value of consistency index significantly larger than the acceptable threshold value of 10%, the proposed elimination method by Slawomir (2016) can be used for reducing inconsistency without changing the judgment of the decision makers. Other challenges encountered in this step includes uncertainty of the response, knowledge gap or lack of problem understanding, which may lead to wrong decisions (Moons *et al*., 2019).

As the above method needs to be calculated repeatedly for each comparison matrix for testing the consistency, and this is a major shortcoming when using CR as the consistency index to compare matrices. This can be solved by using computer software to perform the timely calculation.

In this study, for CR larger than 0.05, the interviewee was asked to consider changing his judgment to a plausible value in range such that the inconsistency could be improved.

For illustration, in Table 6.5, "KPI-7 target IAQ class" has the highest significance with priority vector of 0.74182. The CR is 0.04237 showing it is sufficiently consistent. In Table 6.6 and Table 6.7, indicates that "KPI-2 payback period" has a high significance with a priority vector of 0.85714, and "KPI-4 ratio of actual to target no. of statutory orders removed (%)" has a high significance with a priority vector of 0.88889, where the calculated consistency rate (0) is consistent for all 2-by-2 matrix.

Table 6.5 Pairwise comparisons regarding to the users' perspective

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/5	3	0.18295
KPI-7: Target IAQ class	5	1	8	0.74184
KPI-8: Target workplane illuminance (lux)	1/3	1/8	1	0.07520
			Consistency ratio	0.04237

Table 6.6 Pairwise comparisons regarding to the economic aspect

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	6	0.85714
KPI-3: Investment Cost ($)	1/6	1	0.14286
		Consistency ratio	0.00000

Table 6.7 Pairwise comparisons regarding to the health and safety aspect

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	8	0.88889
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/8	1	0.11111
		Consistency ratio	0.00000

6.3.3 Supermatrix formation (Step 3)

After passing the above inconsistency test, the priorities derived from the comparison matrices will then be added to be the columns of the supermarix of a network (Saaty 2008). Otherwise, the participants need to revise the comparison matrix until passing the inconsistency test. It would be more complicated in the ANP than the AHP since there are more comparisons matrices derived from the following network.

$$W = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_N \\ p_{11}\cdots p_{1n_1} & p_{21}\cdots p_{2n_2} & \cdots & p_{N1}\cdots p_{Nn_N} \end{array} \\ \begin{array}{cc} C_1 & \begin{array}{c} p_{11} \\ \vdots \\ p_{1n_1} \end{array} \\ C_2 & \begin{array}{c} p_{21} \\ \vdots \\ p_{2n_2} \end{array} \\ \vdots & \vdots \\ C_N & \begin{array}{c} p_{N1} \\ \vdots \\ p_{Nn_N} \end{array} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix} \end{array} \qquad \text{(eq.6.11)}$$

When the system has decomposed into N clusters (represented by C_1, C_2 …C_N), and the elements in C_k (where $1 \leq k \leq N$) are p_{knk}, where n_k is the number of elements in C_k cluster. The local priority vectors were entered into the appropriate columns of a supermatrix. It represented the influence priority of an element on the left of the matrix acts on an element at the top of matrix. A standard form of supermatrix is (eq.6.12):

$$W_{ij} = \begin{bmatrix} {w_{i1}}^{ji} & {w_{i1}}^{j2} & \cdots & {w_{i1}}^{jn_j} \\ {w_{i2}}^{j2} & {w_{i2}}^{j2} & \cdots & {w_{i2}}^{jn_j} \\ \vdots & \vdots & \ddots & \vdots \\ {w_{in_i}}^{j1} & {w_{in_i}}^{j1} & \cdots & {w_{in_i}}^{jn_j} \end{bmatrix} \qquad \text{(eq.6.12)}$$

where W_{ij} is a $n_i x n_j$ sub-matrix If there is no relationship between clusters, the corresponding matrix segment is a zero matrix.

6.3.4 Final priorities and selection (Step 4)

To attain a convergence on importance weights, the weighted supermatrix was raised to limiting powers to obtain global priorities in equation (6.13). If there are two or more limiting supermatrices, the final priorities can be found by equation (6.14) (Tzeng and Huang, 2012):

$$\lim_{k \to \infty} W^k \tag{6.13}$$

$$\lim_{k \to \infty} \left(\frac{1}{N}\right) \sum_{j=0}^{N} W_j^k \tag{6.14}$$

where W_j is the jth limiting priority, N denotes the number of limiting supermatrices.

The weighted supermatrix and limit supermatrix obtained are shown in Appendix F. The effects of interdependence in the network can be found in the global priority vector (Appendix G).

Table 6.8 illustrate a section of the limit supermatrix (priority values) obtained from the Super Decision software. The limit supermatrix denote the overall priorities of the indicators, representing the impact of each element on every other element in the network in which they interact (Moons *et al*., 2019).

Table 6.8 A section of limit supermatrix for building retrofit performance evaluation

Clusters	Nodes	KPI-1	KPI-2	KPI-3
Categories	Economic	0.077155	0.077155	0.077155
	Environmental	0.100947	0.100947	0.100947
	Health and Safety	0.126379	0.126379	0.126379
	Users' Perspective	0.12368	0.12368	0.12368
Environmental (Env.)	KPI-1	0.099459	0.099459	0.099459
Economic (Econ.)	KPI-2	0.123583	0.123583	0.123583
	KPI-3	0.054905	0.054905	0.054905
Health and Safety (H&S)	KPI-4	0.077017	0.077017	0.077017
	KPI-5	0.071323	0.071323	0.071323
Users' Perspective (U)	KPI-6	0.077309	0.077309	0.077309
	KPI-7	0.048839	0.048839	0.048839
	KPI-8	0.019404	0.019404	0.019404

6.4 Results

6.4.1 Importance weights of individual KPI

Each interview for pairwise comparison lasted for about 35 minutes on average. The importance weights and corresponding rank of the eight KPIs obtained from 12 interviews are shown in Table 6.9.

On average, the most important KPIs perceived by the interviewees were: KPI 2- payback period (year) (average = 0.184), KPI 4- ratio of actual to target no. of statutory orders removed (%) (average = 0.168) and KPI-1 energy savings (%) (average = 0.165).

By considering the maximum weights of KPI, KPI 2-payback period (year) has the highest value (max.=0.228), followed by KPI 5- ratio of actual to target no. of accidents per year reduced (%) (average = 0.222) and KPI 4- Ratio of actual to target no. of statutory orders removed (%).

By considering the minimum weights of KPI, target indoor air temperature (^{o}C), target IAQ class and target workplane illuminance (lux) got the lowest important weights.

Table 6.9 Importance weights of the individual KPIs and their ranks

Interviewee No.	KPI															
	1		2		3		4		5		6		7		8	
	Energy saving (%)		Payback period (year)		Investment cost ($)		Ratio of actual to target no. of statutory orders removed (%)		Ratio of actual to target no. of accidents per year reduced (%)		Target indoor air temperature (ºC)		Target IAQ class		Target workplane illuminance (lux)	
	W = Weighting; R = Rank															
	W	R	W	R	W	R	W	R	W	R	W	R	W	R	W	R
1	0.152	2	0.126	5	0.144	3	0.211	1	0.141	4	0.124	6	0.082	7	0.020	8
2	0.176	2	0.147	4	0.142	5	0.210	1	0.162	3	0.066	6	0.045	8	0.051	7
3	0.192	2	0.177	3	0.100	5	0.216	1	0.151	4	0.051	7	0.072	6	0.041	8
4	0.135	4	0.184	2	0.128	5	0.125	6	0.197	1	0.140	3	0.050	7	0.041	8
5	0.137	3	0.221	1	0.119	5	0.119	4	0.179	2	0.114	6	0.051	8	0.059	7
6	0.171	2	0.228	1	0.110	5	0.155	3	0.155	3	0.071	6	0.055	7	0.054	8
7	0.174	2	0.216	1	0.096	6	0.135	4	0.125	5	0.135	3	0.085	7	0.034	8
8	0.142	3	0.18	2	0.095	6	0.129	4	0.222	1	0.114	5	0.059	8	0.060	7
9	0.178	3	0.207	1	0.118	5	0.183	2	0.115	6	0.068	7	0.119	4	0.013	8
10	0.175	2	0.154	3	0.124	5	0.212	1	0.142	4	0.060	7	0.119	6	0.014	8
11	0.166	3	0.193	1	0.132	4	0.174	2	0.107	5	0.053	8	0.097	6	0.078	7
12	0.18	1	0.175	2	0.164	3	0.150	4	0.110	5	0.109	6	0.064	7	0.049	8
For KPI	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**	
Average	0.165	-	0.184	-	0.123	-	0.168	-	0.151	-	0.092	-	0.075	-	0.043	-
Median	0.173	2	0.182	2	0.122	5	0.165	2.5	0.147	4	0.090	6	0.068	7	0.045	8
Maximum	0.192	1	0.228	1	0.164	3	0.216	1	0.222	1	0.14	3	0.119	4	0.078	7
Minimum	0.135	4	0.126	5	0.095	6	0.119	6	0.107	6	0.051	8	0.045	8	0.013	8

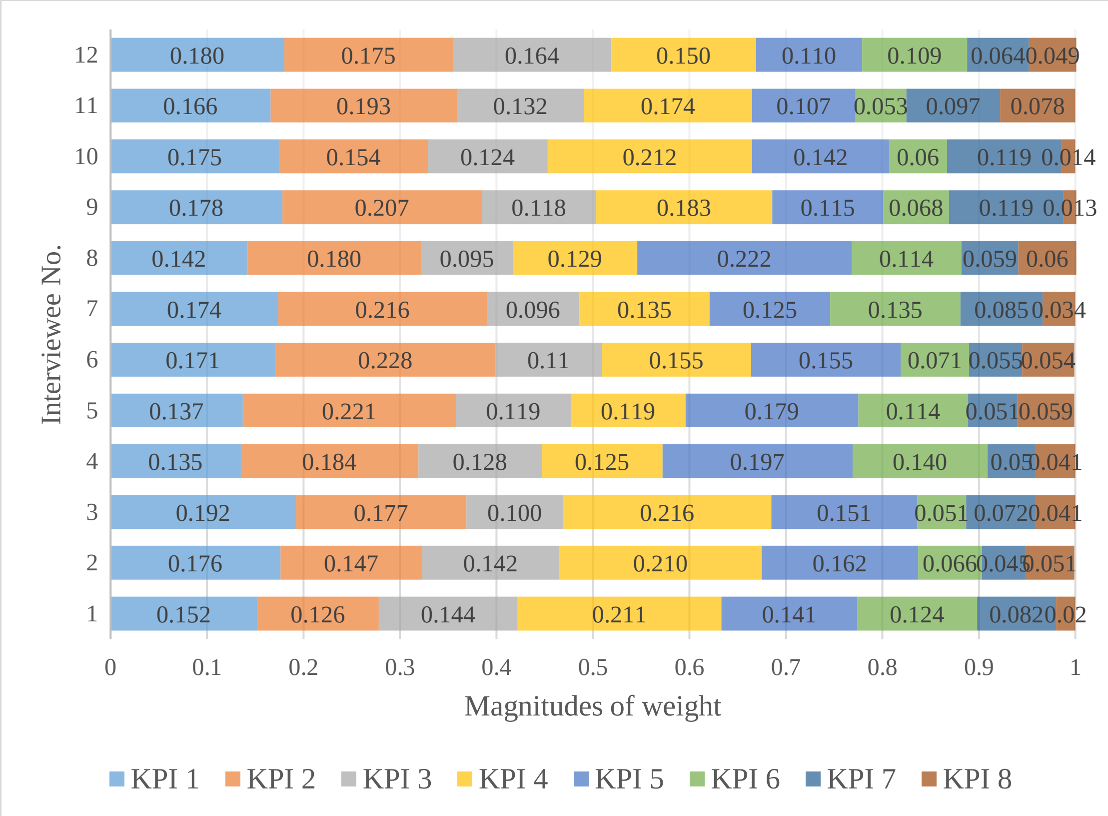


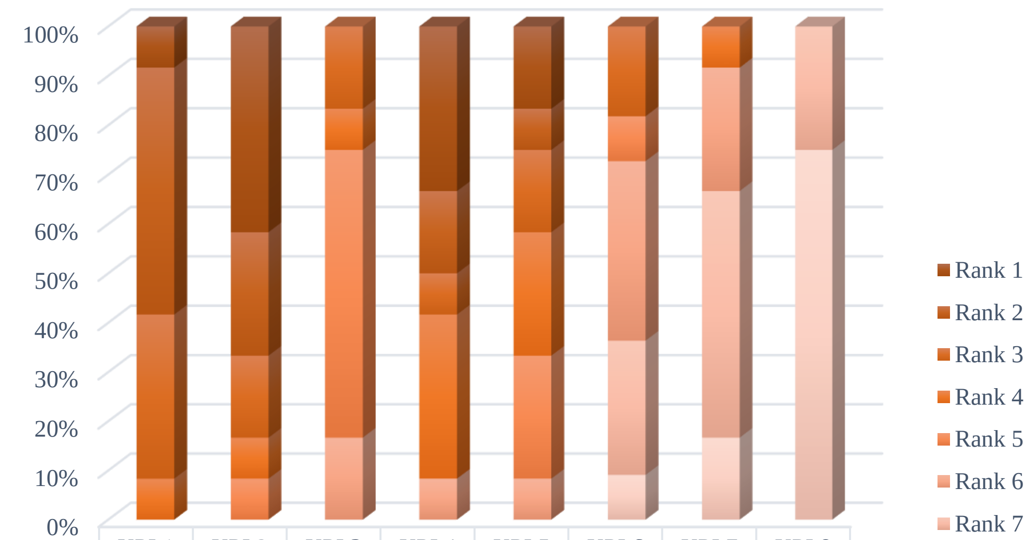
Figure 6.6 Relative differences in magnitudes of weight of KPIs

The relative differences in magnitudes of weight of KPIs is illustrated in Figure 6.6. It shows the relative importance of KPIs from various interviewees. KPI 2 – payback period (year) contributed maximum magnitude of weight (0.228 from interviewee 6); while KPI 8 - Target workplane illuminance (lux) got the lowest weight among all KPIs. For KPI 4 - ratio of actual to target no. of statutory orders removed (%) and KPI 5- ratio of actual to target no. of accidents per year reduced (%), they generally had a lower relative importance weight than KPI-1 and KPI-2, and contributed to moderate relative importance weight.

For KPI 6- Target indoor air temperature (^{o}C), KPI 7-Target IAQ class and KPI 8- Target workplane illuminance (lux), they obviously had a relatively shorted length of bars, with a low to very low importance of weight.

The rank of each KPI is presented in Figure 6.7, showing the percentage of rank counts for each KPIs. 50% of interviewees regarded KPI-2 as rank 1 and 25% of interviewees regarded it as rank 2.

According to the relative importance weights (rank) given by the interviewees, the importance orders of KPI were: KPI-2 (payback period (year)) > KPI 1 (energy savings (%)), KPI-4 (ratio of actual to target no. of statutory orders removed (%)) >KPI-3 (investment cost ($)) > KPI-5 (ratio of actual to target no. of accidents per year reduced (%)) > KPI 6 (target indoor air temperature (°C) > KPI 7 (target IAQ class) > KPI 8 (target workplane illuminance (lux)).



	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8
Rank 1	8.3%	41.7%		33.3%	16.7%			
Rank 2	50.0%	25.0%		16.7%	8.3%			
Rank 3	33.3%	16.7%	16.7%	8.3%	16.7%	16.7%		
Rank 4	8.3%	8.3%	8.3%	33.3%	25.0%		8.3%	
Rank 5		8.3%	58.3%		25.0%	8.3%		
Rank 6			16.7%	8.3%	8.3%	33.3%	25.0%	
Rank 7						25.0%	50.0%	25.0%
Rank 8						8.3%	16.7%	75.0%

Figure 6.7 Percentage of rank counts for individual KPIs

Table 6.10 Median and modes of the ranks of the KPIs

KPI		Median	Mode
1	Energy saving (%)	2	2
2	Payback period (year)	2	1
3	Investment cost ($)	5	5
4	Ratio of actual to target no. of statutory orders removed (%)	2.5	1,4
5	Ratio of actual to target no. of accidents per year reduced (%)	4	4,5
6	Target indoor air temperature (°C)	6	6
7	Target IAQ class	7	7
8	Target workplane illuminance (lux)	8	8

From Table 6.10, it noted that except KPI 4, all other KPIs have a similar rank in median and mode (maximum in difference: 1). For KPI 4- ratio of actual to target no. of statutory orders removed (%), its mode is 1 and 4. It represents that there are two similar group sizes of interviewees perceived that it is either extremely importance (rank 1) or at the moderate importance (rank 4).

6.4.2 Importance weights perceived by different groups

The pattern of the contour for the average importance weights of the KPIs from different parties is shown in Figure 6.8. For the "KPI-2 payback period (year)" and "KPI-3 investment cost", there are large deviations in average relative importance weights of KPIs from interviewees with different job level. The interviewees with directorate grade rated higher (differences: KPI-2: +21%; KPI-3: +15%) for the cost related indicators than the tactical group because they would be more emphasis on whether the retrofit projects are beneficial or worth to be invested. In Figure 6.9, interviewees from non-government organization (NGO) rated much higher for the "KPI-4 ratio of actual to target no. of statutory orders removed (%)" (differences: +19%) than the interviewees who worked in private organizations. It may be due to the fact that the interviewees from private organization have more confident in fulfilling the requirement from statutory orders.

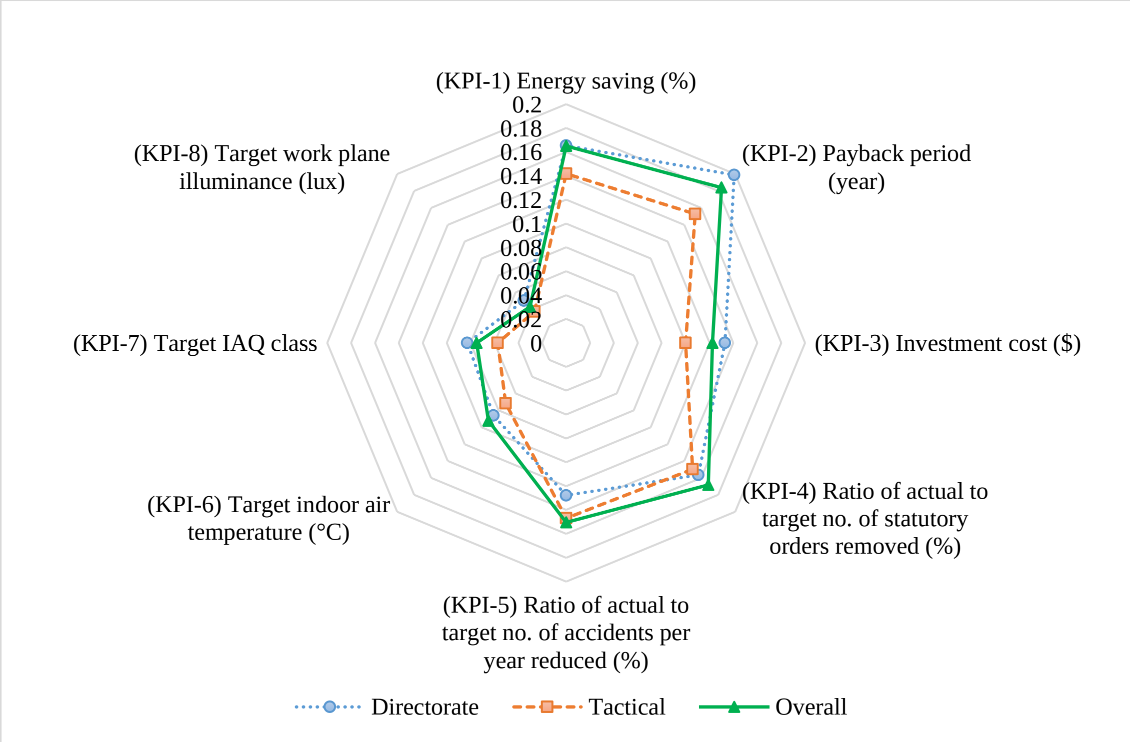


Figure 6.8 Average importance weights of the KPIs given by interviewees with different job titles

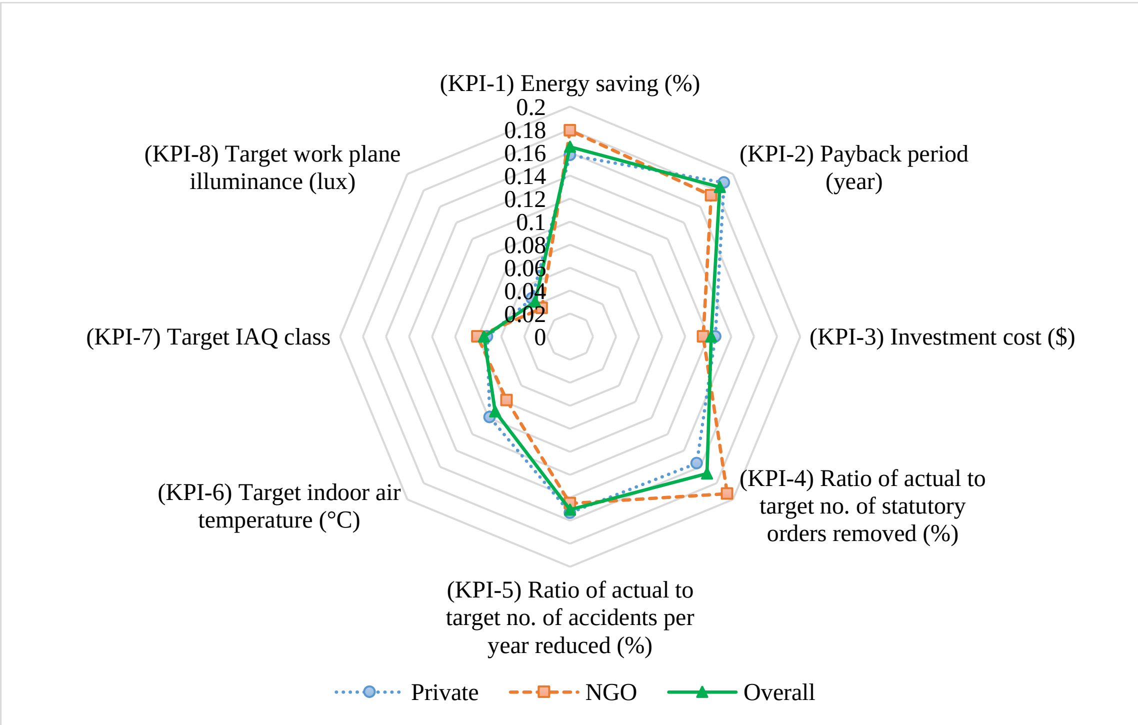


Figure 6.9 Average importance weights of the KPIs given by interviewees with different employees

6.4.3 Importance weight of the four aspects

The importance weights and corresponding rank of the four aspects obtained from 12 interviews are shown in Table 6.11. By comparing with the average weights of four aspects, *Health and Safety* has the highest value (average = 0.350), followed by, *Environmental* (average = 0.219), *Users' Perspective* (average =0.2153) and *Economic* (average =0.2149). It is worth to note that there is one participant (interviewee no. 12) did not agree with the average findings of relative importance weight of the four aspects. He perceived that *Economic* is the most important aspect (value = 0.267) as compared with the *Health and Safety aspect* (value=0.262) and have higher rank (rank =1) than *Health and Safety* (rank 2). He agreed that *Users' Perspective* (average =0.235) rank the last.

Table 6.11 Relative weights among the four aspects

Interviewee No.	Economic		Environmental		Health and Safety		Users' Perspective	
	W = Weighting; R = Rank							
	W	R	W	R	W	R	W	R
1	0.169	4	0.172	3	0.387	1	0.272	2
2	0.200	3	0.260	2	0.397	1	0.144	4
3	0.141	3	0.318	2	0.406	1	0.135	4
4	0.257	2	0.128	4	0.359	1	0.256	3
5	0.299	2	0.139	4	0.333	1	0.229	3
6	0.269	2	0.257	3	0.343	1	0.132	4
7	0.180	4	0.236	3	0.295	1	0.289	2
8	0.158	3	0.155	4	0.403	1	0.285	2
9	0.242	3	0.272	2	0.328	1	0.159	4
10	0.168	4	0.258	2	0.390	1	0.185	3
11	0.231	3	0.203	4	0.302	1	0.265	2
12	0.267	1	0.236	3	0.262	2	0.235	4
Overall	**Economic**		**Environmental**		**Health and Safety**		**Users' Perspective**	
Average	0.2149	-	0.2193	-	0.3504	-	0.2153	-
Median	0.2150	3	0.2359	3	0.3507	1	0.2322	3
Max.	0.2991	1	0.3177	2	0.4057	1	0.2888	2
Min.	0.1413	4	0.1280	4	0.2618	2	0.1317	4

In Table 6.11, by considering the maximum weights of the four aspects, *Health and Safety* the highest value (max.=0.406), followed by *Environmental* (max. = 0.318), *Economic* (max.=0.299) and *Users' Perspective* (max.=0.289).

By considering the minimum value of the four aspects, *Environmental* (min. =0.128) got the lowest value, followed by *Users' Perspective* (min.=0.132), *Economic* (min.=0.141), and *Health and Safety* (min.=0.262).

The relative importance weights of different aspects from participants were shown in Figure 6.10.

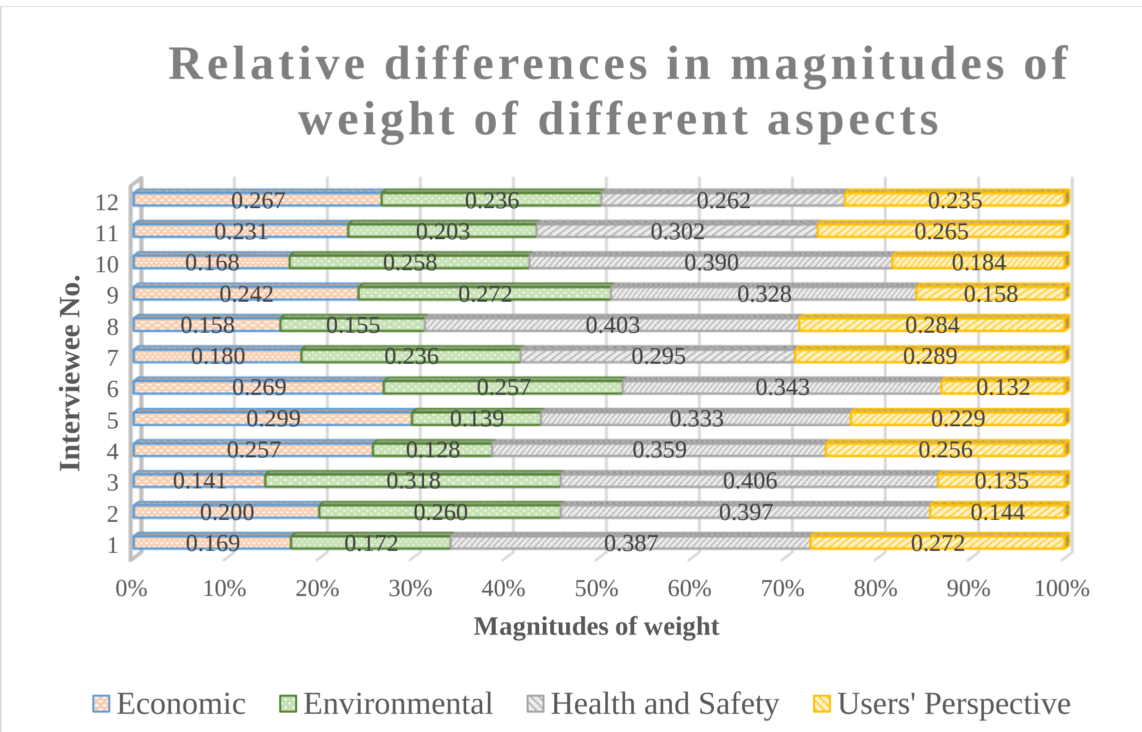
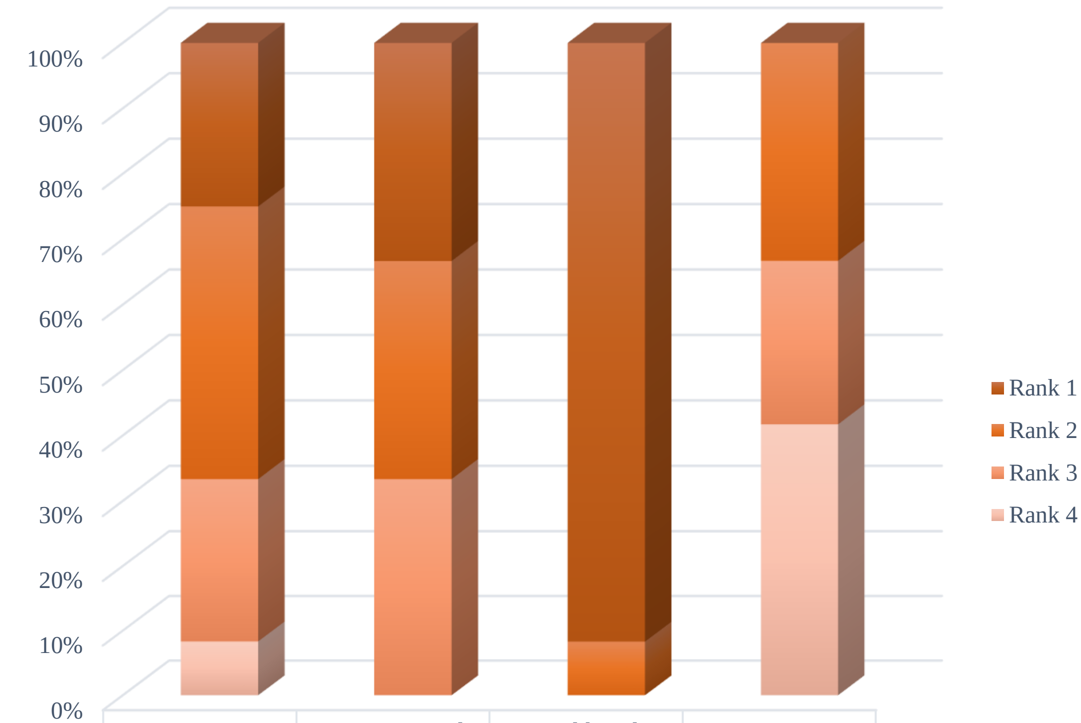


Figure 6.10 Relative differences in magnitudes of weight of each aspect

Figure 6.11 presents the percentage of rank counts for each aspect. As rated by the interviewees, 91.7% of them perceived health and safety as rank 1 and 8.3% of them rated it as rank 2. The importance order was: *Health and safety* > *Economic* > *Environmental* > *Users Perspective*.



	Economic	Environmental	Health and Safety	Users' Perspective
Rank 1	25.0%	33.3%	91.7%	0.0%
Rank 2	41.7%	33.3%	8.3%	33.3%
Rank 3	25.0%	33.3%		25.0%
Rank 4	8.3%	0.0%		41.7%

Figure 6.11 Percentage of rank counts for each aspect

Table 6.12 Median and modes of the ranks of the four aspects

-	Economic	Environmental	Health and Safety	Users' Perspective
Median of ranks obtained	3	3	1	3
Mode of ranks obtained	3	2,3,4	1	4

By the previous findings and observations (Table 6.12), the interviewees perceived that *Health and Safety* is the most important aspect. It is because health and safety of buildings and occupants is essential for proper building functionality before any enhancement of performance by building retrofit works. The remining three aspects (*Economic, Environmental and Users' Perspective*) also with the same median of rank (rank 3) in Table 6.12. To study the relative importance of the remining three aspects, Table 6.13 is shown for illustration. As the three aspects got the same median, same minimum rank and similar weighting in average. They were perceived as almost equally important from by comparison.

Table 6.13 Comparison of the three aspects (excluded Health and Safety)

Aspect	Economic	Environmental	Users' Perspective
Median Ranks	3 (Same)	3 (Same)	3 (Same)
Maximum Rank obtained	1	2	2
Minimum Rank obtained	4 (Same)	4 (Same)	4 (Same)
Overall Rank	2 (33% rank 1-2, 75% rank 3 or above)	3 (33% rank 1-2, 66.67% rank 3 or above)	4 (highest portion 41.67% and majority rank least)
Rank from average	4 (0.215, very close value with 2nd)	2 (0.219)	3 (0.215)
Rank from max. value	3 (0.299)	2 (0.318)	4 (0.289)
Rank from min. value	2 (0.141)	4 (0.128)	3 (0.132)

6.5 Summary

This chapter described a detail account of the research methodology for finding the relative weights of KPIs. Four main steps of ANP were discussed, namely construction of ANP network, pairwise comparisons and local priority vectors, supermatrix formation and final priorities and selection.

After studying the interrelationships between the KPIs, priorities of the criteria were computed based on FM experts' judgment in pairwise comparison. With a total of 12 interviews conducted with professionals, there were more than 300 pairwise comparison. Payback period (year), energy savings (%) and ratio of actual to target number of statutory orders removal (%) were the topmost important KPIs. The other remining three aspects, including economic, environmental and users' perspective were almost in equal importance.

After finding the relative important weights of KPIs, it helped to form the cornerstone for further development of an analytic evaluation scheme for commercial building retrofits performance assessment. In the next chapter, the applicability of the developed method will be further tested by real case studies.

Chapter 7. Building retrofit evaluation: validation

7.1 Introduction

As mentioned in the previous chapter, a unique set of important weights of KPIs from each interviewee were found. This chapter presents the result of the second part of the interviews. Ten case studies with different building characteristics were conducted with the FM professionals, where they indicated the levels of expectation fulfilment of the retrofit projects. The reasons, supportive data and additional information were provided to assist the rating process. This chapter also presents the findings and discussion from the interviews.

7.2 Validation method

To test the developed ANP model and evaluate the overall performance of the retrofit projects, a five-point Likert scale (*1 = Very poor; 2 = Poor; 3 = Fair; 4 = Good; 5 = Very good*) was used in assessing the performance of the eight KPIs (if applicable to the projects). The experienced FM professionals were asked to provide actual values for measuring the commercial building retrofit project practice against the KPIs. The reasons, supportive data and additional information help assist the rating process. The overall weighted score for a case study project was calculated by equation (7.1).

$$BRPI = \frac{\sum_{i=1}^{n}(E_i \times w_e + En_i \times w_{en} + U_i \times w_u + HS_i \times w_{ee})}{100} \quad (7.1)$$

where BRPI is the building retrofit performance index as perceived by the interviewee in stage 4. E is the identified economic indicator, En is the environmental indicator, U is the indicator of user comfort, HS is the indicator for health and safety, w is the weighting factor (%) corresponding the indicator number i. The sum of weighting is 100%.

7.3 Validation procedures

7.3.1 Collect information about the selected buildings (Step 1)

Basic information for the sampled commercial buildings were collected from the interviewees in Chapter 6, and ten different cases were contained and illustrated, including the types of premises, age of building, number of storeys, area (total gross floor area and internal floor area). The detail of the retrofit measures adopted, the project starts and end dates, cost break down and project costs were also collected (Table 7.1), which including various type of premises such as office, composition of office and retail, or office with other types (such as exchange or telebet centre). The age of buildings ranged from 5 to 44 years. The number of storeys for the commercial buildings ranged from 6 to 39 (high-rise building), and with single or twins-tower. The total gross floor areas of the buildings ranged from 2,800m^2 (small scale) to 115293m^2 (large scale).

Some of the data required were inapplicable for the retrofit project. The interviewees spent extra effort and time to collect these data when evaluating the building retrofit performance. Two of the buildings were unavailable for case studies. To complete the evaluation and ensure full understanding of the research, follow-up actions such as emails and phone calls were required to ensure all the required information was obtained. These extra information and effort were very useful for providing and showcasing the applicability of the established evaluation method.

Table 7.1 Background information about the sampled buildings

Interviewee No.	Building code	Type of premises	Age of building	No. of storeys	Total Gross floor area (m^2)	Internal floor area (m^2)
1	-	-	-	-	-	-
2	B2	Retail (Mall)	24	6	~83,364	~70,860
3	B3	Office + Others (Training Centre, Telebet Centre, Broadcasting Studios)	5	9 [3 (office) + 2 (broadcasting studios) + 3 (telebat centre) + 1 (training centre) + 1 (canteen)]	56,971	60,767
4	Alexandra House	Office + Retail	44	39 [2 (office) + 37 (retail)]	46,000	48,000
5	B5	Office + Retail	30	31 [28 (office) + 1 (retail) + 2 (carpark)]	65,900	85,800
6	B6	Office + Retail	37	34 [25 (office) + 3 (retail) + 6 (carpark)]	33,100	-
7	Administration Building (Western Area at Kowloon Side)	Office	12	23 [22 (office) + 1 (carpark)]	2,800	17,600
8	Gateway I	Office + Retail	26	2x [33 (Office) + 2 (Retail) + 1 Carpark]	1,241,000(ft^2)/115,293m^2	-
9	B9	Office + Other (Exchange)	31	27 [6(exchange) + 18 (offices) + 3 (carpark/mechanical)]	13,194	14,905
10	Building 5W in Science Park	Office	18	6	17,506	190,811
11	-	-	-	-	-	-
12	Building 2W, Hong Kong Science Park	Office	16 (since 2004)	9 [8 (office) + 1 carpark (89 spaces)]	31,316	20,675

Table 7.2 shows different kind of retrofit measures in commercial buildings. For examples, these can be grouped into 1. lighting installation replacement, 2. chiller plant and or AHU replacement, 3. sprinkler pipe replacement and or F.S. panel upgrade, 4. water pump and or waste-water pipe replacement and 5. others (e.g. escalator replacement, lift modernization). Most of the projects were started a few years ago, ranging from year 2014 to still ongoing project. The project costs were varied from $0.63M-$81M.

Table 7.2 Other information about the sampled buildings

<table>
<tr><th>Building code</th><th>Retrofit measures adopted</th><th>Start/End date</th><th>Cost</th><th>Project cost</th><th>Other information</th></tr>
<tr><td rowspan="6">B2</td><td>1. LED replacement</td><td>Jan 19 – April 19</td><td>$0.4M</td><td colspan="2" rowspan="6">-/ Lift modernization, BMS revamping, CCTV upgrade, PAU/AHU/FCU replacement. Comply with BEEC Cap 610’s CoP recommendation on chiller plant selection.
Due to COVID-19 all PAUs have to be operated for 24 hours, instead of from 10am to 10 pm. (refer to actual data, no energy saved, but extra consumed)</td></tr>
<tr><td>2. Chiller plant replacement</td><td>Jan 19 – Oct 19</td><td>$42M</td></tr>
<tr><td>3. Sprinkler pipe replacement</td><td>Mar 19 – May 19</td><td>$0.35M</td></tr>
<tr><td>4. Repartitioning works</td><td>Oct 19 – Mar 20</td><td>$32M</td></tr>
<tr><td>5. Signage upgrade</td><td>18 – 19</td><td>$2M</td></tr>
<tr><td>6. Escalator replacement</td><td>2019 - 2024</td><td>$3000M</td></tr>
<tr><td rowspan="5">B3</td><td>1. 1. Adopting Motion Control LED Lighting in Back of House Areas</td><td>Dec 18 – Sep 19</td><td>$400,000</td><td colspan="2" rowspan="5">$0.63M/
Installing Automatic Condenser Tubes Cleaning System for Water Cooled Chillers.</td></tr>
<tr><td>2. Improving Chiller Plant CHW Delta Temperature</td><td>Mar 19 – Apr 19</td><td>$150,000</td></tr>
<tr><td>3. Optimizing Fresh Air Supply in Kitchen & Canteen</td><td>Sep 17 – Dec 17</td><td>$80,000</td></tr>
<tr><td>4. Rescheduling Hot Water System Sterilization during off peak period</td><td>Sep 19 – Sep 19</td><td>$0</td></tr>
<tr><td>5. Rescheduling Fresh Air Fans and Exhaustive Air Fans Operating</td><td>Mar 19 – Apr 10</td><td>$0</td></tr>
</table>

(Cont')

Building code	Retrofit measures adopted	Start/End date	Cost	Project cost	Other information
B4	1. Replacement of lift system	Jan 15- June 16	$6,000,000	$81M	-
	2. Replacement of AHU system	Jan 19- June 21	$45,000,000		
	3. Replace with energy efficient lamp	Jan 16- Dec 19	$3,000,000		
B5	1. Replace with energy efficient lamp	Jan 14 – Dec 15	$210,000	$5.31M	-
	2. Replacement work of air cool chiller plant	Jan 15 – April 16	$4,520,000		
	3. Replacement of a new portable water pumps	Oct 17 – April 18	$580,000		
B6	1. Replace with energy efficient lamp	-	-	$25M	-
	2. Replacement work of chiller water pipe	-	-		
	3. Lift Modernization	2012-2015	-		
B7	1. Replace with energy efficient lamp	May 18-Dec 18	$250,000	$0.8M (including on cost overhead)	-
	2. Replacement work of chiller water pipe	Mar 18-April 19	$360,000		
	3. Replacement of a chiller water pipe insulation for AHU PAU systems	Oct 17-April 19	$160,000		
B8	Replacement work of chillers (Chiller 1-2)	Practically completed on Dec 17 and Jan 18 (Chiller 1 & 2)	$9,016,000	$19.3555M	-
	Replacement work of chillers (Chiller 3-5)		$10,339,500		
B9	1. Chiller Replacement	Jan 13-Aug 13	$6.3M	$11.4M	-
	2. Wastewater pipe replacement	14-17	$2.5M		
	3. Carpark flooring refurbishment	Nov 17-Dec 17	$0.5M		
	4. FS AFA Panel upgrade	Mar 18-April 18	$0.3M		
	5. Main Switchboard replacement	Jun 19-March 20	$1.8M		
B10	1. Replace one chiller with cooling load upgraded to 300 ton	Jan 20 -June 20	$2,100,000	$2.2M	-
	2. Replacement work of LED lights	Mar 19-April 19	$100,000		
B12	1. Installation of Smart Wireless Carpark Lighting System for Carparks 187/16	Jun 16 – April 18	$135,000	$0.605058M	-
	2. Replacement of Existing Light Fitting with LED Light Fitting for all Staircases 169/16	Sep 16 - Mar17	$394,570		
	3. Replacement of High Bay Lighting by LED Lighting Fitting at Loading Bay 222/17	Sep 17 – May 18	$75,488		

7.3.2 Perform individual evaluation (Step 2)

To further monitor the performance of building after retrofit completion and study any improvement on it, the interviewees, who were responsible to manage the retrofit project, were invited to evaluate their project by five-point scale in various aspects. The reasons, supportive data and other relevant information were also included. The details for building retrofit performance rating are shown in Table 7.3A-7.3J (Building code: B2-B10, B12).

Table 7.3A Evaluation form for case study (B2)

KPIs \ Building Code	B2		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	-		-
B) Economic Aspects			
KPI-2 Payback period (year)	-		-
KPI-3 Investment cost ($)	-		-
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-		-
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-		-
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 24-26°C; Achieved & Δ: 100% Fulfil the target	5	In most of the time, shopping arcade and common area can achieve target air temperature (24-16°C) during operation hours.
KPI-7 Target IAQ class	Achieved and Target = Good Class (100% Fulfil the target)	5	Good Class certificate for IAQ was issued by the EPD in 2019-2020.
KPI-8 Target workplane illuminance (lux)	-		-

Table 7.3B Evaluation form for case study (B3)

Building Code / KPIs	B3		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	Δ= 6.5%	4	Electricity consumption per total area was reduced 6.5%.
B) Economic Aspects			
KPI-2 Payback period (year)	The overall payback period of all retrofit projects is around 2 years.	3	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs. For others, data from digital power analyzers are adopted to perform post measurement and verification.
KPI-3 Investment cost ($)	Total investment cost: $630,000 Target investment cost: $ 550,000 Δ = +14.5% (over budget)	4	Two NO COST energy measures were carried out in order to reduce the overall payback period.
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	Achieved and Target = 1 orders (100% Fulfil the target)	5	Statutory order regarding to unauthorized building works was removed.
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	Achieved and Target = 1 person (100% Fulfil the target; people are now free from Legionnaires' disease)	5	From record, fewer people took sick leave as well after retrofit (e.g. reduction of air pollutants due to HVAC retrofit).
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 23.5°C; Achieved: 23.5°C (>80% frequency); Δ: 100% Fulfil the target	5	In most of the time, office area can achieve target air temperature (23.5°C) during office hours.
KPI-7 Target IAQ class	Achieved and Target = Good Class (100% Fulfil the target)	5	Good Class certificate for IAQ was issued by the EPD in 2015-2019.
KPI-8 Target workplane illuminance (lux)	-	-	-

Table 7.3C Evaluation form for case study (B4)

KPIs \ Building Code	B4		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	Δ= 5%	4	N/A
B) Economic Aspects			
KPI-2 Payback period (year)	The estimated simple payback for LED retrofit: 15 years; HVAC retrofit: 5 years	3	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs. For HVAC retrofit, it has 2 to 5 years payback expectation based on an initial energy audit.
KPI-3 Investment cost ($)	Total investment cost: $62M Target investment cost: $ 81M	4	To incorporating many other sustainability performance
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	Achieved and Target = 0 order (100% Fulfil the target)	5	Statutory order regarding to fire safety components
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	Achieved and Target = 0 person (100% Fulfil the target; people are now free from Legionnaires' disease)	5	From record, fewer people took sick leave as well after retrofit (e.g. reduction of air pollutants due to HVAC retrofit).
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 24°C; Achieved: 23.5°C	5	In most of the time, office area can achieve target air temperature (23.5°C) during office hours.
KPI-7 Target IAQ class	Achieved and Target = Excellent Class (100% Fulfil the target)	5	Excellent Class certificate for IAQ was issued by the EPD
KPI-8 Target workplane illuminance (lux)	Achieved and Target = average 500 lux (100% Fulfil the target)	5	The occupants reflected that the visual comfort was highly improved. They can now work more efficiently.

Table 7.3D Evaluation form for case study (B5)

Building Code / KPIs	B5		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	10.33%	4	Electricity consumption per total area was reduced from 142kWh/m^2 to 127 kWh/m^2.
B) Economic Aspects			
KPI-2 Payback period (year)	The actual simple payback for LED retrofit: 7 years; HVAC retrofit: 12 years Pumping: 15 years	3	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs. For HVAC retrofit, it over 10 years payback based on 2 years actual site power consumption.
KPI-3 Investment cost ($)	Total investment cost: $5,310,000 Target investment cost: $ 4,938,000 Δ = +7.0% (over budget)	4	In order to use better performance chiller plant so, it is changed another brand of chiller plant, so the cost had been adjusted.
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	NA	-	No order
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	NA	-	No accident so far
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 22.5°C; Achieved: 22.5°C (>85% frequency) Δ: 100% Fulfil the target	5	In most of the time, office area can achieve target air temperature (22.5°C) during office hours.
KPI-7 Target IAQ class	NA	-	No apply IAQ
KPI-8 Target workplane illuminance (lux)	Achieved and Target = average 450 lux (100% Fulfil the target)	5	The users no complaint the lux level reduced from 600 to 450 lux.

Table 7.3E Evaluation form for case study (B6)

KPIs \ Building Code	B6		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	No info	-	No info
B) Economic Aspects			
KPI-2 Payback period (year)	The actual simple payback for LED retrofit: 2 years; HVAC retrofit: 3 years	4	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs, overall life span vs payback period. For HVAC retrofit, it has 2 to 5 years payback expectation based on an initial energy audit.
KPI-3 Investment cost ($)	Total investment cost: around HK$300,000 for LED around HK$2,000,000 for MVAC	4	-
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-	-	-
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-	-	-
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 23.5°C; Achieved: 23.5°C (>80% frequency); Δ: 100% Fulfil the target	5	In most of the time, office area can achieve target air temperature (23.5°C) during office hours.
KPI-7 Target IAQ class	Achieved and Target = Excellent Class (100% Fulfil the target)	5	Excellent Class certificate for IAQ was issued by the EPD in 2017-2018. (Retrofit done in late 2016)
KPI-8 Target workplane illuminance (lux)	Achieved and Target = average 500 lux and 200 lux for office and common corridor respectively. (100% Fulfil the target)	5	The occupants reflected that the visual comfort was highly improved. They can now work more efficiently.

Table 7.3F Evaluation form for case study (B7)

KPIs \ Building Code	B7		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	About 6.5% against the consultant's estimation at 5%	4	Electricity consumption was reduced according to the electricity bill payment
B) Economic Aspects			
KPI-2 Payback period (year)	The acceptable payback for LED retrofit: 7 years; HVAC retrofit: 8 years	3	To payback period was debated in the management board and finally accepted.
KPI-3 Investment cost ($)	Total investment cost: $800,000 Target investment cost: $ 700,000 Δ = +14.2% (over budget)	3	Additional cost was incurred from (1) control advancement on HVAC and (2) equipment selection on high end product instead of lowest price bid.
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	Achieved and Target = 1 order (100% Fulfil the target)	5	Statutory order regarding to cooling tower COP was removed.
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	Achieved and Target = 0 person (100% Fulfil the target; people are now free from Legionnaires' disease)	5	From record, zero fatal accident at workplace after completion of retrofit work
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	Target: 25°C; Achieved: 25.5 °C (>70% frequency); Δ: 100% Fulfil the target	4	In most of the time, office area can achieve target air temperature (25.5°C) during office hours in target measurement points.
KPI-7 Target IAQ class	Achieved and Target = Good Class (100% Fulfil the target)	5	Good Class certificate for IAQ is maintained
KPI-8 Target workplane illuminance (lux)	Achieved and Target = average 500 lux (100% Fulfil the target)	5	No complaint was received so far from end users on workplace's lux level

Table 7.3G Evaluation form for case study (B8)

KPIs \ Building Code	B8		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	^Please refer to attached	4	^Please refer to attached
B) Economic Aspects			
KPI-2 Payback period (year)	^Please refer to attached	3	^Please refer to attached
KPI-3 Investment cost ($)	^Please refer to attached	4	^Please refer to attached
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-	-	-
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-	-	-
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	According to Energy Saving Charter signed	5	According to Energy Saving Charter signed
KPI-7 Target IAQ class	Excellent Class for all Office Buildings & Good Class for shopping malls	5	Excellent Class for all Office Buildings & Good Class for shopping malls
KPI-8 Target workplane illuminance (lux)	According to CIBSE Guide	5	According to CIBSE Guide

Table 7.3H Evaluation form for case study (B9)

KPIs \ Building Code	B9		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	Achieved / target = 1247961/1829271 = 68%	3	Achieved saving is lower than the target saving.
B) Economic Aspects			
KPI-2 Payback period (year)	The actual simple payback for chiller replacement: 5 years;	4	4 years payback expectation based on an initial energy calculation.
KPI-3 Investment cost ($)	Within Budget	4	Actual cost met the budget
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-	-	-
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-	-	-
D) Users' Perspective			
KPI-6 Target indoor air temperature (ºC)	-	-	-
KPI-7 Target IAQ class	-	-	-
KPI-8 Target workplane illuminance (lux)	-	-	-

Table 7.3I Evaluation form for case study (B10)

Building Code / KPIs	B10		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	Δ= [(2,885,484 - 2,642,385)/2,642,385] kWh = 9.20%	4	-
B) Economic Aspects			
KPI-2 Payback period (year)	The simple payback for LED retrofit: 4 years; HVAC retrofit: 8.6 years	3	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs. For HVAC retrofit, it has 5 to 7 years payback expectation based on an initial energy audit.
KPI-3 Investment cost ($)	Total investment cost: $2,200,000 Target investment cost: $ 2,500,000 Δ = -13.64% (within budget)	4	To incorporating many other sustainability performance features necessary to achieve a better rating and it is necessary to replace it due to frequently failure rate.
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-	-	-
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-	-	-
D) Users' Perspective			
KPI-6 Target indoor air temperature (ºC)	Target: 23.5ºC; Achieved: 23.5ºC (>80% frequency) Δ: 100% Fulfil the target	5	In most of the time, office area can achieve target air temperature (23.5ºC) during office hours.
KPI-7 Target IAQ class	Achieved and Target = Excellent Class (100% Fulfil the target)	5	Excellent Class certificate for IAQ was issued by the EPD in 2019-2020.
KPI-8 Target workplane illuminance (lux)	Achieved and Target = average 500 lux (100% Fulfil the target)	5	The occupants reflected that the visual comfort was highly improved. They can now work more efficiently.

Table 7.3J Evaluation form for case study (B12)

Building Code / KPIs	B12		
	Actual values	**Scores**	**Reasons**
A) Environmental Aspects			
KPI-1 Energy saving (%)	Δ= (4,037,426kWh-3,767,412kWh)/4,037,426kWh = 6.69%	4	-
B) Economic Aspects			
KPI-2 Payback period (year)	In terms of electrical saving (assume $1.1/ kWh) = 297,015 Payback period = (605,058/297,015) = 2year	4	For LED retrofit, a nominal of 2 years payback is expected. And in consider current rate can extend the lamp replacement life. The work is justified
KPI-3 Investment cost ($)	Total investment cost: $605,058 Target investment cost: $ 860,000 Δ = -29.6% (within budget)	4	To incorporating many other sustainability performance features and the tender sum is far within budget. The work is justified.
C) Health and Safety			
KPI-4 Ratio of actual to target no. of statutory orders removed (%)	-	-	There is no statutory order in place for the proposed improvement.
KPI-5 Ratio of actual to target no. of accidents per year reduced (%)	-	-	The work is unrelated to reduce accident.
D) Users' Perspective			
KPI-6 Target indoor air temperature (°C)	-	-	The work is not affecting indoor temperature.
KPI-7 Target IAQ class	-	-	The work is not affecting IAQ.
KPI-8 Target workplane illuminance (lux)	-	-	The illuminance level (output lamp power) does not change.

7.3.3 Summary of the performance evaluations

From the above ten case studies, they were evaluated by different KPIs of various aspects, ranging from using two to all KPIs, and covering one to all the four aspects. In Table 7.4, it concluded that nearly all cases, 90% of them applied all the environmental and economic KPIs (KPI-1 energy saving (%), KPI-2 payback period (year) and KPI-3 investment cost ($)) to evaluate the building retrofit performance. A few cases (B3, B4 and B7) also applied the health and safety indicators (KPI-4 ratio of actual to target no. of statutory orders removed (%) and KPI-5 ratio of actual to target no. of accidents per year reduced (%)) in the evaluation. For users' perspective, majority (60-80%) of the cases applied KPI-6 target indoor air temperature (^{o}C), KPI-7 target IAQ class and KPI-8 target workplane illuminance (lux).

Table 7.4 Summary of the performance evaluation

KPI	Building Code									
	B2	B3	B4	B5	B6	B7	B8	B9	B10	B12
Environmental										
1		√	√	√	√	√	√	√	√	√
Economic										
2		√	√	√	√	√	√	√	√	√
3		√	√	√	√	√	√	√	√	√
Health and Safety										
4		√	√			√				
5		√	√			√				
Users 'Perspective										
6	√	√	√	√	√	√	√		√	
7	√	√	√		√	√	√		√	
8			√	√	√	√	√		√	

7.3.4 Calculate the overall weighted performance scores (Step 3)

As rated the performance scores from professionals, the overall weighted performance scores for buildings (Table 7.5) can be calculated by the derived equation (7.1).

Table 7.5 Overall weighted performance scores of sampled buildings

Blgs	KPI																	
	KPI-1 Energy saving (%)		KPI-2 Payback period (year)		KPI-3 Investment cost ($)		KPI-4 Ratio of actual to target no. of statutory orders removed (%)		KPI-5 Ratio of actual to target no. of accidents per year reduced (%)		KPI-6 Target indoor air temperature (ºC)		KPI-7 Target IAQ class		KPI-8 Target workplane illuminance (lux)		Overall Score	Building Retrofit Performa-nce Index
	W	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**		**BRPI**
1	0.152	-	0.126	-	0.144	-	0.211	-	0.141	-	0.124	-	0.082	-	0.020	-	-	-
2	0.176	-	0.147	-	0.142	-	0.210	-	0.162	-	0.066	5	0.045	5	0.051	-	5.000	100%
3	0.192	4	0.177	3	0.100	4	0.216	5	0.151	5	0.051	5	0.072	5	0.041	-	4.327	86.5%
4	0.135	4	0.184	3	0.128	4	0.125	5	0.197	5	0.14	5	0.05	5	0.041	5	4.368	87.4%
5	0.137	4	0.221	3	0.119	4	0.119	-	0.179	-	0.114	5	0.051	-	0.059	5	3.928	78.6%
6	0.171	-	0.228	4	0.110	4	0.155	-	0.155	-	0.071	5	0.055	5	0.054	5	4.349	87.0%
7	0.174	4	0.216	3	0.096	3	0.135	5	0.125	5	0.135	4	0.085	5	0.034	5	4.067	81.3%
8	0.142	4	0.180	3	0.095	4	0.129	-	0.222	-	0.114	5	0.059	5	0.060	5	3.988	79.8%
9	0.178	3	0.207	4	0.118	4	0.183	-	0.115	-	0.068	-	0.119	-	0.013	-	3.648	73.0%
10	0.175	4	0.154	3	0.124	4	0.212	-	0.142	-	0.060	5	0.119	5	0.014	5	4.060	81.2%
11	0.166	-	0.193	-	0.132	-	0.174	-	0.107	-	0.053	-	0.097	-	0.078	-	-	-
12	0.180	4	0.175	4	0.164	4	0.150	-	0.110	-	0.109	-	0.064	-	0.049	-	4.000	80.0%
Overall																		
Aver.	0.165	-	0.184	-	0.123	-	0.168	-	0.151	-	0.092	-	0.075	-	0.043	-	4.174	83.5%
Median	0.173	4	0.182	3	0.122	4	0.165	5	0.147	5	0.090	5	0.068	5	0.045	5	-	-
Max.	0.192	4	0.228	4	0.164	4	0.216	5	0.222	5	0.14	5	0.119	5	0.078	5	-	-
Min.	0.135	3	0.126	3	0.095	3	0.119	5	0.107	5	0.051	4	0.045	5	0.013	5	-	-

From Table 7.5, the building retrofit performance index (BRPI) for each individual project indicates the performance level of the retrofit projects as given by the FM professionals. Higher its performance score, better the actual retrofit performance was, and the shorter performance gap was achieved for that project.

The BRPI of the above case studies ranged from 73% to 100%, with a mean score of 83.5%. The KPIs regarding health and safety aspects were not applicable in most of the above retrofit projects (e.g. B2,B5,B6,B8,B9 and B10), except building B4 and B7. The BRPI were for B4 and B7 were higher than 80%, and all KPIs were applicable in these two projects.

For building B2, only KPI-6 and KPI-7 out of the eight indicators were applicable due to its project nature. This project mainly aims at improving the users' perspective such as target air temperature and IAQ class, where other aspects were not highly emphasized on. Both KPIs in B2 had a score of 5, resulting in 100% in BRPI.

For building B3 and B9, KPI-8 (target work plane illuminance) was not applicable in the assessment because the projects did not involve any retrofitting of lighting installation. The BRPI for B3 and B9 were 86% and 73% respectively.

To study the score of each KPI, they ranged from 3 (*fair*) to 5 (*very good*). For energy savings (%), the majority of interviewees (87.5%) rated it as 4 (*good*). For economic aspect, 38.9% of the economic KPIs was scored as 3 (*fair*) and 61.1% of them were scored as 4 (*good*). For health and safety aspect, all the KPIs had a score of 5 (*very good*). For users' perspective, except one professional rated 4 (*good*) for KPI-6 Target indoor air temperature (^{o}C), all the others (95.2%) also had a score of 5 (*very good*). The average overall score from all cases was 4.174 (83.5%), representing "good" performance for the retrofit works.

7.4 Discussion on the interview findings

A large project may include various kind of retrofit measures. The developed analytic method allows performance evaluation for common retrofit measures such as replacement of chiller, AHU, lighting installation, etc. The applicability of the eight KPIs were examined by ten case studies. Figure 7.1 shows the consideration for adopting building retrofit measures.

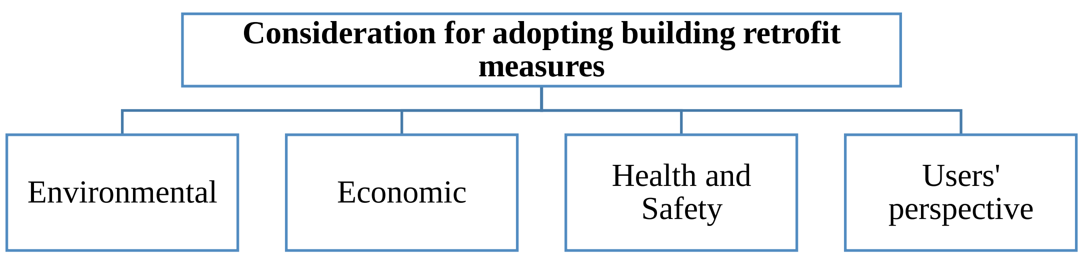


Figure 7.1 Consideration for adopting building retrofit measures

An interviewee stated that *"some private companies may emphasize more on payback period and investments costs than other parties, but some of the equipment's life span is shorter than its payback period (KPI-2). From the perspective of facility management, life cycle cost is also another important parameter). Take installation of PV panels as an example, when considering about its costs, it also includes maintenance fee such as change of rectifiers (e.g. requires maintenance for every four years; need to perform maintenance* *twice during its life cycle), disposal fee, electricity fee (e.g. 4-5 HKD per kW) and incentive (get the 'feed-in tariff' FIT from energy suppliers.). However, it can only provide a rough estimation on life cycle cost in real practice for such a long (30-40 years) building lifespan.*" Therefore, payback period (KPI-2) (which also includes the consideration of life cycle cost in the estimation) and investment costs (KPI-3) are two important KPIs for project evaluation. The feedback from the interviewee also matched with the finding in Ho et al. (2021)'s study, whose results show that the indicator "life cycle cost ($)" was in high importance and rank third among 52 indicators in focus group study and ranked seven among 19 indicators in another industry-wide survey. It was replaced by another indicator, investment cost ($), for simplification in performance evaluation.

Regarding another aspect - health and safety aspect, an interviewee stated that "*some old commercial buildings (with building ages: 30 to 40 years) are essential to improve the provision of facilities, such as addition of fire services doors and removal of unauthorized works. In various buildings, it may not pose immediate risk from that such as water slippage, improper or insufficient provision of fire services installation. However, health and safety is an essential part as compared with other aspects (economic, environmental and users' perspective). They cannot be compared when filling the pairwise comparison matrices as health and safety should not be sacrificed and it is essential to meet the basic legal requirement.*" Therefore, the interviewee suggested to compare these three aspects (economic, environmental and users' perspective) separately with health and safety. Therefore, more health and safety KPIs can be listed out and being used for detail analyses in these old buildings or similar projects.

Another interviewee also stated that "*functionality of equipment (e.g. system stability, reliability, and safety) can be a prime concern in the real practice. For example, lift upgrade or lift modernization for passengers' safety will also be taken place despite its high price. After renovation, it can provide more reliable service and reduce the risk of accidents. In addition, some retrofit projects were carried out primely due to equipment failure or upgrading its old design*". Therefore, it is possible to focus mainly on one important aspect only - health and safety in some retrofit projects.

From architectural and users' points of view, an interviewee commented that "*more vivid outlook, fashionable design and better image with good management and hygiene may lead to higher rental value in commercial buildings.*" This has been stated in Carlson and Pressnail (2018)'s study that the market value can be increased from external look improvement and energy class upgrade. From the detailed case studies of four large commercial office buildings, energy retrofitting can decrease operating costs, increase occupancy rates, and increase effective rent (rental revenue) and therefore increasing net operating income. Furthermore, Mecca *et al.* (2020) studied the extraordinary maintenance impact on the property values in the real estate market. By performing whole building energy efficiency upgrading, improvement of the outlook and maintenance status of its facades, these partly contributed to an increase in the average price of the pre-intervention sales by 25%, and specifically 10% of apartment price increase due to energy rating jump (e.g. from energy rating of F to A). Another increase of 15% was due to improvement in the general state of preservation and maintenance for the buildings. On the other hand, the retrofit projects may also take place despite its high investment cost.

An interviewee further elaborated that "*client's and tenants' may still proceed the retrofit measures despite of its higher price or additional cost of investment. It is because renovation can attract more shoppers and visitors in shopping arcade and retail shops. Renovation without payback may also be done as customers perspective is their top concern. On the other hand, renovation may not be necessary if clients want to minimize the disruption of business operation caused by renovation.*" Therefore, the eight KPIs in the developed assessment method may not be all applicable, depending on its project nature. The applicability of indicators depends on the resources (e.g. financial, technological and labour) that are available and the quality of service that should be achieved (Preiser and Nasar, 2008).

As reported by Miller and Buys (2008), in-depth interviews with smaller organizations were performed and found that tangible proof and detailed cost analyses of specific sustainability features were wanted to be seen. However, the industry may still have limited knowledge of specific sustainability features. Hence, more business cases were needed to be further developed. Case studies of this research serve as practical examples to shorten the gap between the theoretical and industrial practice. This study also provides more insight for FM practitioners in assessing the retrofit performance for commercial buildings.

7.5 Summary

The second part of the in-depth interviews were conducted for method validation. The building retrofit performance of commercial buildings were evaluated with the eight KPIs and the FM professionals were asked to rate the performance on the applicable aspects. Self-evaluations were conducted by the interviewed FM professionals, where they indicated the levels of expectation fulfilment of the retrofit projects. The self-evaluated scores for the building retrofit performance were more than 4.00 (good), which implied that the overall project outcomes were satisfactory after performing retrofit works.

Finally, from the discussion in the interview, an interviewee suggested that although life cycle cost was an important parameter, it can be difficult to provide an accurate prediction for such a long building life cycle (e.g. 30 to 40 years). When estimating the cost for installation of PV panels, it included maintenance fee for change of rectifiers, disposal fee, electricity fee and incentive from energy supplier. Therefore, payback period (year) (KPI-2), which included the consideration of life cycle cost in the estimation, was used as an economic KPI for project evaluation. Furthermore, the applicability of KPIs were project-based, for example, improvement in economic, environmental and users' perspective aspect were prime concern for some retrofit projects (e.g. shopping mall), while functionality and health and safety aspect can be the prime concern in old buildings. Conclusion, recommendations, and future works are coved in the next chapter.

Chapter 8 Conclusions and recommendations

8.1 Introduction

Numerous studies have been conducted on evaluation of building retrofits, the methods for which include simulations, estimations, and field investigations into some particular aspects. However, there remains limited empirical and comprehensive performance evaluation studies on building retrofits. In this research, a rigorous performance evaluation method was developed to evaluate the retrofit performance of commercial buildings in Hong Kong. The methodology of developing the analytical method was demonstrated. This chapter concludes the major findings and limitations of this research. Recommendations and future works are also suggested at the end.

8.2 Major findings

This study consists of four stages. In Stage 1, a four-stage systematic literature review was conducted using the approach of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. As reviewed, frequently adopted retrofit measures were related to improvement on building envelop (83%), HVAC (46%) and renewable energy (25%). Among the previous studies, nearly half of the studied buildings (46%) were residential buildings and nearly one-third were commercial buildings. Their major focuses in performance evaluation were on the environmental aspect (77%) and the economic aspect (64%), while less than one-fifth were related to the users' perspective (17%).

Based on the literature review, 62 performance indicators that were relevant to measurement of the retrofit performance were identified. As some of these indicators bear the same meaning, they were consolidated to become 52 indicators. These indicators were classified into four aspects, namely economic, environmental, health and safety, and users' perspective.

In Stage 2, ten FM professionals participated in a focus group study. Despite their high ranking and mean importance score, some of the performance indicators identified in the previous stage were removed for reasons of "no record data", "too time consuming to work out", "too costly to work out" and/or other specific reasons (e.g. "uncommon and inapplicable in practice"). 19 performance indicators were shortlisted for inclusion in the analytic method at the preliminary stage, including three indicators suggested in the focus group study.

In Stage 3, an industry-wide online survey was conducted to further investigate the important levels of shortlisted performance indicators and solicited the opinions of professionals who managed building retrofit projects. The results were positive that all the 19 indicators had an average score of 3 (moderate) on a five-point Likert scale. Responses of the participants were grouped according to gender, work experience, nature of organization, role of employer, job level and academic qualification. From a series of U-test, H-test and Spearman rank correlation analyses on the perceived importance levels of the indicators, no significant differences were observed between the various groups of respondents, except for a few cases: female considered life cycle cost ($) as more important than the male did; FM practitioners at the tactical level, when compared with those at the strategic level, perceived that three of the indicators in the users' perspective category were more important; the veteran practitioners, when compared with the freshmen, considered that normalized energy savings (kWh/m^{2}year) was less important. Regarding the indicators' ranking, practitioners with different natures of organization, roles of employer and work experiences had different emphases as well. Nevertheless, the manageability of the indicators was improved by refinement prior to developing the intended analytic method for assessing retrofit performance. As applying all the shortlisted indicators may require considerable effort and resources, eight KPIs were finalized, namely: energy savings (%), payback period (year), investment cost ($), ratio of actual to target number of statutory orders removed (%), ratio of actual to target number of accidents reduced, target indoor air temperature (^{o}C), target indoor air quality (IAQ) class, and target workplane illuminance (lux). In addition, respondents commented that high evaluation cost, difficulty of getting precise estimation, and variation in project nature were the main difficulties in evaluating building retrofit performance. While manual data collection for analyzing the performance of building systems can be tedious, time consuming and inaccurate, the advancement of building information modeling (BIM) and smart sensors may overcome these hurdles in future (Kamari *et al.*, 2021; Mantha *et al.*, 2016).

In Stage 4, 12 in-depth interviews with competent FM professionals were conducted to demonstrate the applicability of an analytic network process (ANP) in finding out the relative importance weights for the KPIs. Different sets of such relative importance weights were found from the interviews. On average, payback period (year), energy saving (%) and ratio of actual to target no. of statutory orders removed (%) were perceived as the three most important KPIs. Given that the conditions and characteristics of commercial buildings were unique, the retrofit performance of each sampled building was self-evaluated by a FM professional, who managed the retrofit project. The results from ten case studies validated the applicability of the established evaluation method. Meanwhile, the weakness of this method and difficulties encountered in the validation process were also revealed.

To conclude, a considerable number of studies have been conducted in evaluating the performance of building retrofits, but research that aims to develop an analytic method for assessing the holistic performance of building retrofits was limited. In addressing this research gap, the study reported above was completed successfully. It helped to identify feasible KPIs for building retrofit evaluation; encourage the disclosure of retrofit information; improve the existing theoretical frameworks and developed an analytic method for facilities managers to evaluate their retrofit projects. The methodology of this study can also be taken as reference for similar KPI studies on other building types or research domains.

8.3 Limitation

Due to the lack of publicly available benchmarks of building retrofit KPIs, the established analytic method for assessing retrofit performance was limited to self-assessment. According to the British Standards Institution (2018) BS EN ISO 9004:2018(E), self-assessment can "*provide an overall view of performance of an organization and the degree of maturity of its management system. The results of self-assessment can be a valuable input into management reviews. It also has the potential to be a learning tool, which can provide an improved overview of the organization, promote the involvement of interested* *parties and support the overall planning activities of the organization. The information gained from the self-assessment can also be used to benchmark with other organizations, stimulate comparisons and share learning throughout the organization, and monitor progress by conducting periodic self-assessments*". Therefore, developing benchmarking for building retrofits can help to examine whether the retrofit performance is better or worse than the average level. Yet, there are many influential factors that can affect the evaluation, such as building ages, characteristics, and organization structures. And there are many difficulties in developing such benchmarking, for example, demanding works on data collection, privacy issue and difficulty in collecting sensitive data (e.g. investment cost) (Man *et al*., 2015).

During the identification process for KPIs, labelling, grouping and addition of KPIs were done through the personal perceptual filters of the FM respondents of this study. Thus, the results were based on the "own experience" of the respondents with subjective interpretation. Nevertheless, this has been improved by undergoing a series of rigorous studies (focus group study, industry-wide survey, and in-depth interviews) and the responses solicited were checked with quality assurance (e.g. by consistency check when using the ANP method).

Regarding the industrial-wide survey in Stage 3, respondents who worked in the government had different perceptions from those who worked for private companies or non-governmental organizations (NGOs). The users' perspective was highly regarded by the respondents who worked in the government, while the economic aspect and energy savings were the major considerations for the respondents from the private sector. According to the British Standards Institution (2018), self-evaluation should be performed by personnel at appropriate levels and top management. Although none of the interviewees in Stage 4 worked in the government that managed commercial buildings owned by the government, self-evaluations were performed by other FM professionals from the private sector or NGOs. This ensured the validity of the retrofit performance assessment results obtained from the established method.

8.4 Recommendations and future works

Finally, there are some suggestions for future research. An analytic method for assessing retrofits performance in commercial buildings in Hong Kong was developed and validated in this study. It is applicable to be used in evaluating typical retrofit works, such as replacement of chillers and lighting installation. However, due to the unique and special characteristics of certain retrofit projects, some of the KPIs used for the established method may be inapplicable to some retrofit works (e.g. fire services panel upgrading, lift modernization, replacement of electrical main switch boards, repartitioning). To cater for the evaluation for such works, this analytic method may further be enriched by developing different sets of KPIs. For example, health and safety may be the main concern in old buildings renovation. A separate set of KPIs on health and safety (e.g. i) ratio of actual to target no. of statutory orders removed (%); ii) ratio of actual to target no. of accidents reduced per year (%); iii) ratio of actual to target no. of lost workdays reduced per year (%); iv) ratio of actual to target no. of health and safety complaints reduced per year (%)) may be applied to this kind of projects. For retrofit projects that mainly aim at improving building interior (e.g. repartitioning), KPIs such as “increase in occupants’ satisfaction (%)”

and “increase of building value (%) (KPI-17)” may be used. By enriching the scope and diversity of the KPIs in different lists, the practitioners will have more choices to choose the most suitable KPIs for evaluating their retrofit projects. All in all, this study provided insights into the way forward for further development of KPIs for evaluation of different kinds of retrofit projects.

On the other hand, incentives from local governments are usually used to motivate building owners or building professionals to evaluate their retrofit projects. Through considering all the assessment criteria from “Wastewi$e Certificate”, “Energywi$e Certificate”, ”IAQwi$e Certificate” and “Carbon Reduction Certificate” that were newly launched in 2020 in Hong Kong, a similar benchmark for assessing the overall improvement from deep energy retrofit (DER) can also be established. Similarly, the benchmark for DER can be set into three levels: “basic”, “good” or “excellent”. It can help to increase business competitiveness by attracting those customers who value companies that are committed to improving building environmental quality and enhancing corporate image (Environmental Campaign Committee and Environmental Protection Department, 2021a;b;c;d). However, there is still a long way to go for examining its feasibility before such benchmarks could be established.

Lastly, as revealed from the literature review for this study, ANP has been frequently applied in performance evaluation in construction companies and research and development projects (Kheybari *et al*, 2020). This study has attempted to shorten the gap between literature and real practice by developing and validating an ANP-based method for assessing retrofits performance in commercial buildings. Another software, Data Envelopment Analysis (DEA), is an evaluation tool that can handle multiple inputs and outputs, without requiring assumptions for functional form and distribution type in advance (Lin and Tseng, 2005, Mardani *et al*., 2017). Yet, there has been limited research on how an appropriate DEA model may be developed in assessing the retrofit performance of engineering facilities in commercial buildings. Note that the feasibility of using such a model needs to be further studied because comparison can only be made for buildings with the same set of retrofit works, which is difficult to find among a group of building samples (e.g. retrofit measures – cannot be directly compared due to different combinations of retrofit measures, locations – different weather conditions can affect energy saving performance). Different retrofit projects, each with a unique set of retrofit measures with different characteristics, are often not directly comparable. Although evaluating a single retrofit measure by DEA is more simple, it is still a timely process and it requires prior approval from building owners to collect such data. These would be constraints and barriers that future studies of this kind have to overcome.

Appendix A.

Questionnaire and information for focus group meeting

Questionnaire on identification of key performance indicators for assessing retrofit performance in commercial buildings

This questionnaire comprises 3 sections.

Section 1 contains questions on the personal particulars of the participants.

Section 2 please indicate the importance levels of the listed indicators for evaluating the retrofit performance in commercial buildings.

Section 3 seeks for any other comments the participants may have.

<u>Section 1</u>

Please fill in the following items and tick the appropriate boxes below.

1.1 Gender

□ Male □ Female

1.2 Working experience

_____________ years

1.3 Employer

□ Government □ Non-government public organization □ Private company

1.4 Job title

____

1.5 Buildings / premises that you have worked on

□ Office □ Retail □ Hotel □ Others (please specify: ______________)

1.6 Professional qualification

□ Full member of: □ BSOMES □ HKIE □ CIBSE □ ASHRAE □ HKIFM □ IFMA

□ Others (please specify: _____________)

1.7 Highest academic qualification

□ Associate degree / diploma / certificate

□ Bachelor degree

□ Master degree

□ Doctorate degree □ Others (please specify: ______________________________)

Section 2

2.1 Please circle a number **(1-5)** that represents the **importance level of each listed indicator** **for evaluating the retrofit performance in commercial buildings** after listening to the presentation of the facilitator.

2.2 Please ☑ **tick the appropriate boxes** (Yes or No) to indicate whether the indicators should be **included in the retrofit assessment**.

If you consider the indicator should not be included, please also specify the reasons (Note: **can be more than one reason**)

Indicators		**(1.) Importance level**	**(2.) Should it be included in assessment?**	
		1: Very low 2: Low 3: Moderate 4: High 5: Very high	Yes	No (Reasons): a. No record data b. Too time consuming to work out c. Too costly to work out d. Others (please specify)
A.) Economic Aspect				
E1	Payback Period (year)	1 2 3 4 5	Y☐	N☐ / ________________
E2	Return on Investment (%)	1 2 3 4 5	Y☐	N☐ / ________________
E3	Internal rate of return (%)	1 2 3 4 5	Y☐	N☐ / ________________
E4	Net present value ($)	1 2 3 4 5	Y☐	N☐ / ________________
E5	Weighted Average Cost of Capital (%)	1 2 3 4 5	Y☐	N☐ / ________________
E6	Peak demand savings ($)	1 2 3 4 5	Y☐	N☐ / ________________
E7	Mean cost of intervention saved ($/kWh)	1 2 3 4 5	Y☐	N☐ / ________________
E8	Annual energy cost savings($/year)	1 2 3 4 5	Y☐	N☐ / ________________

Indicators		(1.) Importance level	(2.) Should it be included in assessment?	
		1: Very low 2: Low 3: Moderate 4: High 5: Very high	Yes	No (Reasons): a. No record data b. Too time consuming to work out c. Too costly to work out d. Others (please specify)
E9	Profit ($)	1 2 3 4 5	Y☐	N☐ / ________________
E10	Net Cash Flow ($/year)	1 2 3 4 5	Y☐	N☐ / ________________
E11	Investment cost ($)	1 2 3 4 5	Y☐	N☐ / ________________
E12	Normalized investment cost ($/m^2)	1 2 3 4 5	Y☐	N☐ / ________________
E13	Retrofit and operation costs ($)	1 2 3 4 5	Y☐	N☐ / ________________
E14	Global Cost ($/m^2)	1 2 3 4 5	Y☐	N☐ / ________________
E15	Life Cycle Cost ($)	1 2 3 4 5	Y☐	N☐ / ________________
E16	Revocability Cost ($)	1 2 3 4 5	Y☐	N☐ / ________________
B.) Environmental Aspect				
En1*	Δ Carbon emission (%)	1 2 3 4 5	Y☐	N☐ / ________________
En2*	Δ Carbon emission (kg$CO_{2\text{-}eq}$/m^{2}year)	1 2 3 4 5	Y☐	N☐ / ________________
En5	CO_2 emission payback periods	1 2 3 4 5	Y☐	N☐ / ________________
En6	Global warming potential	1 2 3 4 5	Y☐	N☐ / ________________
En7	Emission class indices	1 2 3 4 5	Y☐	N☐ / ________________
En8	Energy savings (%)	1 2 3 4 5	Y☐	N☐ / ________________
En3*	Δ Normalized energy savings (kWh/m^{2}year)	1 2 3 4 5	Y☐	N☐ / ________________

Indicators		(1.) Importance level	(2.) Should it be included in assessment?	
		1: Very low 2: Low 3: Moderate 4: High 5: Very high	Yes	No (Reasons): a. No record data b. Too time consuming to work out c. Too costly to work out d. Others (please specify)
En10	Energy generation (%)	1 2 3 4 5	Y☐	N☐ / ________________
En11	Energy payback periods	1 2 3 4 5	Y☐	N☐ / ________________
En12	Reduction of electrical peak demand (%)	1 2 3 4 5	Y☐	N☐ / ________________
En13	Reduction of peak cooling load (%)	1 2 3 4 5	Y☐	N☐ / ________________
En4*	Δ Electricity consumption per year (kWh/year)	1 2 3 4 5	Y☐	N☐ / ________________
En5*	Δ Normalized energy consumption (kWh/m^{2}year; kWh/m^{2}month)	1 2 3 4 5	Y☐	N☐ / ________________
En16	Energy consumption class	1 2 3 4 5	Y☐	N☐ / ________________
En17	Total site energy (GJ)	1 2 3 4 5	Y☐	N☐ / ________________
En18	Life Cycle Analysis	1 2 3 4 5	Y☐	N☐ / ________________
C.) Health and Safety				
HS1*	Target % in removal of statutory orders	1 2 3 4 5	Y☐	N☐ / ________________
HS2*	Target % in reduction of number of accidents per year	1 2 3 4 5	Y☐	N☐ / ________________
HS3*	Target % in reduction of number of legal cases per year	1 2 3 4 5	Y☐	N☐ / ________________

Indicators		(1.) Importance level	(2.) Should it be included in assessment?
		1: Very low 2: Low 3: Moderate 4: High 5: Very high	Yes No (Reasons): a. No record data b. Too time consuming to work out c. Too costly to work out d. Others (please specify)
HS4*	Target % in reduction in number of compensation cases per year	1 2 3 4 5	Y☐ N☐ / _______________
HS5*	Target % in reduction in amount of compensation paid per year	1 2 3 4 5	Y☐ N☐ / _______________
HS6*	Target % in reduction in number of health and safety complaints per year	1 2 3 4 5	Y☐ N☐ / _______________
HS7*	Target % in reduction in number of lost workdays per year	1 2 3 4 5	Y☐ N☐ / _______________
HS8*	Target % in reduction in number of incidents of specific disease per year	1 2 3 4 5	Y☐ N☐ / _______________
D.) Users' perspective			
U1*	∆ Predicted Mean Vote (PMV) index	1 2 3 4 5	Y☐ N☐ / _______________
U2*	∆ Predicted Percentage of Dissatisfied (PPD) (%)	1 2 3 4 5	Y☐ N☐ / _______________
U3*	∆ Indoor air temperature (^{o}C)	1 2 3 4 5	Y☐ N☐ / _______________
U4*	∆ Discomfort hours in summer (%)	1 2 3 4 5	Y☐ N☐ / _______________
U5*	Thermal comfort level	1 2 3 4 5	Y☐ N☐ / _______________

Indicators		(1.) Importance level	(2.) Should it be included in assessment?
		1: Very low 2: Low 3: Moderate 4: High 5: Very high	Yes No (Reasons): a. No record data b. Too time consuming to work out c. Too costly to work out d. Others (please specify)
U6*	∆ Ventilation and infiltration rates (h^{-1})	1 2 3 4 5	Y☐ N☐ / ________________
U7*	∆ Indoor CO_2 levels/ other harmful substances (ppm)	1 2 3 4 5	Y☐ N☐ / ________________
U8*	Internal air quality	1 2 3 4 5	Y☐ N☐ / ________________
U9*	Work productivity	1 2 3 4 5	Y☐ N☐ / ________________
U10*	∆ Workforce performance (dollars/m^2)	1 2 3 4 5	Y☐ N☐ / ________________
U11*	∆ Work plane illuminance (lux)	1 2 3 4 5	Y☐ N☐ / ________________
U12*	∆ Equivalent continuous weighted sound pressure level (dBA)	1 2 3 4 5	Y☐ N☐ / ________________

Other suggested indicators for building retrofit evaluation:

____

____

Section 3:

Other comments:

------End------

Thank you!

Appendix:

The meaning and details of indicators can be referred below (total: 52 indicators).

A.) Economic Indicators (16 indicators)

No.	Indicators
E1	Payback Period (year)
E2	Return on Investment (%)
E3	Internal rate of return (%)
E4	Net present value ($)
E5	Weighted Average Cost of Capital (%)
E6	Peak demand savings ($)
E7	Mean cost of intervention saved ($/kWh)
E8	Annual energy cost savings($/year)
E9	Profit ($)
E10	Net Cash Flow ($/year)
E11	Investment cost ($)
E12	Normalized investment cost($/m^2)
E13	Retrofit and operation costs ($)
E14	Global Cost ($/m^2)
E15	Life Cycle Cost ($)
E16	Revocability Cost ($)

B.) Environmental Indicators (16 indicators)

Δ: Difference between target and actual

No.	Indicator (original)	No.	Indicator (consolidated or new)
En1	Reduction in carbon emissions (%)		
En2	Reduction in greenhouses gases (Mt of $CO_{2\text{-eq}}$)	En1*	Δ Carbon emission (%)
En3	Carbon emission (normalized) ($kgCO_{2\text{-eq}}/m^2year$)	En2*	Δ Carbon emission ($kgCO_{2\text{-eq}}/m^2year$)
En4	Greenhouse gas emissions (normalized) ($kgCO_{2\text{-eq}}/m^2year$)		
En5	CO_2 emission payback periods		-
En6	Global warming potential		-
En7	Emission class indices		-
En8	Energy savings (%)		-
En9	Normalized energy savings (kWh/m^2year)	En3*	Δ Normalized energy savings (kWh/m^2year)
En10	Energy generation (%)		-
En11	Energy payback periods		-
En12	Reduction of electrical peak demand (%)		-
En13	Reduction of peak cooling load (%)		-
En14	Electricity consumption per year (kWh/year)	En4*	Δ Electricity consumption per year (kWh/year)
En15	Normalized energy consumption (kWh/m^2year; kWh/m^2month)	En5*	Δ Normalized energy consumption (kWh/m^2year; kWh/m^2month)
En16	Energy consumption class		-
En17	Total site energy (GJ)		-
En18	Life Cycle Analysis		-

C.) Health and Safety (8 indicators)

No.	Indicators	No.	Indicator (consolidated or new)
HS1	Removal of statutory orders	HS1*	Target % in removal of statutory orders
HS2	Reduction in number of accidents per year	HS2*	Target % in reduction of number of accidents per year
HS3	Reduction in number of legal cases per year	HS3*	Target % in reduction of number of legal cases per year
HS4	Reduction in number of compensation cases per year	HS4*	Target % in reduction in number of compensation cases per year
HS5	Reduction in amount of compensation paid per year	HS5*	Target % in reduction in amount of compensation paid per year
HS6	Reduction in number of health and safety complaints per year	HS6*	Target % in reduction in number of health and safety complaints per year
HS7	Reduction in number of lost workdays per year	HS7*	Target % in reduction in number of lost workdays per year
HS8	Reduction in number of incidents of specific disease per year	HS8*	Target % in reduction in number of incidents of specific disease per year

D.) Users' Perspective (12 indicators)

No.	Indicators	No.	Indicator (consolidated or new)
U1	Predicted Mean Vote (PMV) index	U1*	Δ Predicted Mean Vote (PMV) index
U2	Predicted Percentage of Dissatisfied (PPD) (%)	U2*	Δ Predicted Percentage of Dissatisfied (PPD) (%)
U3	Indoor air temperature (°C)	U3*	Δ Indoor air temperature (°C)
U4	Discomfort hours in summer (%)	U4*	Δ Discomfort hours in summer (%)
U5	Thermal comfort level [best, good, acceptable, unacceptable]	U5*	Thermal comfort level (to be determined)
U6	Ventilation and infiltration rates (h^{-1})	U6*	Δ Ventilation and infiltration rates (h^{-1})
U7	Indoor CO_2 levels/ other harmful substances (ppm)	U7*	Δ Indoor CO_2 levels/ other harmful substances (ppm)
U8	Internal air quality	U8*	Internal air quality (to be determined)
U9	Work productivity	U9*	Work productivity (to be determined)
U10	Workforce performance (dollars/m^2)	U10*	Δ Workforce performance (dollars/m^2)
U11	Work plane illuminance (lux)	U11*	Δ Work plane illuminance (lux)
U12	Equivalent continuous weighted sound pressure level (dBA)	U12*	Δ Equivalent continuous weighted sound pressure level (dBA)

A.) <u>Economic Indicators</u>

No.	Indicators
E1	**Payback Period (year)** The static investment payback period refers to the time required to recover the project investment by project profits without considering the time value of money, and described by the following formula (Liu *et al.*, 2018): $$\sum_{t=0}^{P_t}(CI-CO)_t = 0$$ Where CI: cash input CO: cash output (CI-CO): net cash flow the *t*th year For project's financial viability, by comparing P_t and reference static investment payback period P_C, if $P_t < P_C$ can be recovered. If $P_t > P_C$, the financial evaluation results cannot be accepted.
E2	**Return on investment (ROI) (%)** ROI of an intervention is generally expressed (Jankovic, 2019): $$ROI = \frac{(Benefit - Cost)}{Cost} \times 100[\%]$$
E3	**Internal rate of return (IRR) (%)** It refers to the discount rate when project's financial Net Present Value (NPV) is 0, and can be calculated by the following equation (Liu *et al.*, 2018): $$\mathrm{NPV(IRR)} = \sum_{t=0}^{n}(CI-CO)_t(1+IRR)^{-t} = 0$$ Where n: project's lifetime, CI: cash input CO: cash output Project financial viability can be evaluated by comparing IRR and the hurdle cut-off rate (i_c). If IRR $\geq i_c$, the project is economically acceptable. If IRR$\leq i_c$, the project should be rejected.
E4	**Net present value (NPV) ($)** NPV can be expressed as follows (Song *el al.*, 2017): $$NPV = -I + \sum_{n=0}^{LS}\frac{S_n}{(1+r)^n}$$ $$S_n = S_0(1+p)^n$$

	Where I: initial investment, LS: lifespan of the building n: time period S_n: savings of year n S_0: initial saving r: cost of capital (%) p: increase rate An investment should be undertaken only when NPV is > 0. The best solution comes to the highest NPV scenario in a fixed lifespan.
E5	**Weighted Average Cost of Capital (WACC) (%)** International Research Journal of Finance and Economics ISSN 1450-2887 Issue 45 (2010) It can be expressed as follows (Rehman and Raoof, 2010): $WACC = W_d K_d (1\text{-}T) + W_e K_e$ Where W_d: weightage of debt in capital K_d: cost of debt W_e: weightage of equity in total capital K_e: cost of equity [To calculate WACC, it needs to know (i) the gearing ratio (how much of the capital is raised from debt or equity); (ii) the cost of debt (include bank loans and bond instruments. For borrowers of bank loans, it used fixed or floating interest rates. For issuers of bonds, it usually used fixed interest rates – the dividend yields.) (iii) the cost of equity (the rate of return required by equity investor).] Example: <table><tr><td></td><td>No.</td><td>Charge</td><td>Capital structure</td><td>Cost</td><td>Average cost</td></tr><tr><td>Loan</td><td>1000</td><td>5%</td><td>2/3 = 0.667</td><td>0.667x0.05 = 0.033</td><td>0.0833 (require 8.3% IRR for viable project)</td></tr><tr><td>Equity</td><td>500</td><td>15%</td><td>1/3 = 0.333</td><td>0.333x0.15=0.05</td><td></td></tr></table>
E6	**Peak demand savings ($)** It associated with avoiding the construction of new power plants (Krarti, 2015).
E7	**Mean cost of intervention saved ($/kWh)** The total cost of saved electricity.
E8	**Annual Energy Cost savings ($/year)** The energy cost savings per year from the implementation of retrofit project.
E9	**Profit ($)** Revenue is from selling the generated electricity to the grid (Leal *et al.*, 2015).

E10	**Net cash flow (NCF) ($/year)** The NCF for renewable energy technology scenarios considering the cost, and income due to the surplus of power generation (PVP systems), can be expressed as follows (Gugul *et al.*, 2018): $$\mathrm{NCF}_j^{PVP} = \mathrm{CI}_j^{PVP} - \mathrm{CO}_j^{PVP} = (t_{e,j}(E_{PVP} - E_{PVP,c}))$$ Where NCF_j^{PVP}: net cash flow of PVP system in year j, USD/year CI_j^{PVP}: cash inflow of PVP system in year j, USD/year CO_j^{PVP}: cash outflow of PVP system in year j, USD/year $t_{e,j}$: average electricity price estimate in year j, USD/kwh E_{PVP}: electricity generated by PVP system, kWh/year $E_{PVP,c}$: electricity consumed by PVP system, kWh/year
E11	**Investment cost ($)** The total amount of money spent for the retrofit project.
E12	**Normalized investment cost ($/m^2)** The amount of money spent for the retrofit project per meter square.
E13	**Retrofit and Operation costs (i.e. energy cost)** For building replacements, generation equipment replacements, generation equipment O&M and the bill of the energy drawn from the grids (Leal *et al.*, 2015).
E14	**Global cost (GC) ($/m^2)** It can express as follows (Ascione *et al.*, 2017): $$GC = IC + RC - INC + OC_h + OC_c + OC_{DHW} + OC_{el} - OC_{SRES}$$ Where IC: initail investment costs RC: replacement costs of the retrofit measures INC: discounted public financial incentives OC: discounted lifecycle operating costs (for space heating (OC_h), space cooling (OC_c), domestic hot water production (OC_{DHW}), direct electric uses (OC_el) and the OC saving due to the energy provided by renewable energy sources systems (OC_{SRES})).
E15	**Life Cycle Cost (LCC) ($)** The LCC can be calculated as follows (Luddeni *et al.*, 2018): $$LCC = IC+EC*USPW$$ Where IC: investment cost EC: energy cost (electricity and natural gas) USPW: uniform series present worth factor (where USPW =$[1-(1+r_d)^{-N}]/r_d$; r_d is the real discount rate to 3%) N: lifetime of retrofitted buildings set to 20 years

E16	**Revocability Cost ($)** It relates to the propensity that future costs can vary over time in a building across its estimated life. Factors influencing revocability cost include the physical characteristic of the object, sunkness of initial investment, technological innovation and economics of learning regarding substitutes in the future (Tokede *et al.*, 2018). Examples of revocability scenarios in buildings include **'energy costs reduction due to installation of passive systems, renewable systems or energy-efficient gadgets', 'security cost reduction due to automation of building entry and exit controls', and 'maintenance cost reduction due to improved data retention and management using systems such as Building Information Modelling (BIM)** (Tokede *et al.*, 2018).

B.) Environmental Indicators

No.	Indicators
En1	**Percentage of reduction in carbon emissions (%)** Percentage of reduction in carbon emissions ($CO_{2\text{-eq}}$).
En2	**Reduction in greenhouses gases (GHG) (Mt of $CO_{2\text{-eq}}$)** Total reduction in greenhouse gases (such as carbon dioxide, methane, nitrous oxide and ozone) in terms of $CO_{2\text{-eq}}$.
En3	**Carbon emission index (kg CO_2/m^2year)** The annual CO_2 emission per meter square before retrofit.
En4	**Greenhouse gas emissions (normalized) (kgCO_2eq/m^2-year)** Annual greenhouse gases emission per meter square from the retrofit.
En5	**CO_2 emission payback periods** It is the period between CO_2 emitted due to construction equals the reduction of CO_2 emisssion due to system operation. It can be expressed as follows (Huang *et al.*, 2012): $$T_{CO2} = \frac{M_l}{M_o}$$ Where T_{CO2}(Y) is payback time of CO_2 M_l (kg-CO_2) is CO_2 emissions due to construction of system M_o(kg-CO_2) is annual reduction of CO_2 emissions due to system operation
En6	**Global warming potential (GWP) (kg $CO_{2\text{-eq}}$)** The annual global warming potential, measure of how much heat a greenhouse gas traps in the atmosphere during retrofitting, relative to carbon dioxide. A general equation for annual GWP related to heating energy of a building is: $$\sum_{i=0}^{n} \frac{a_i GWP_i}{L_i} + \frac{Q \times EF}{\omega} = 0$$ Where a_i: gross amount of energy efficient measures (EEMs) used; GWP_i: global warming potential of EEMs L_i: life-time of EEM; Q: annual heating energy consumption EF: primary GWP factor of heating device ω : corresponding heating system efficiency

	(e.g. EF for condensing oil-fired boiler: 0.319 kg CO_{2eq}/kWh; condensing gas-fired boiler: 0.258g CO_{2eq}/kWh; gas-fired combined heat and power: 0.115g CO_{2eq}/kWh; electric brine-water heat pump: 0.641g CO_{2eq}/kWh; low-temperature boiler for gas combustion: 0.277g CO_{2eq}/kWh)
En7	**Emission class indices** An example of the greenhouse gases emission performance (GEP) for single family houses is illustrated as follows (Gugul *et al.*, 2018):
En8	**Energy savings (%)** The percentage of energy saving from retrofit projects.
En9	**Normalized energy savings (kWh/m^2 year)** The amount of energy saved per year per meter square from retorfit projects.
En10	**Energy generation (%)** Percentage of energy generated by the retrofit measures, e.g. using photovoltaic (PV) panels.
En11	**Energy payback periods** It is the period between energy consumption due to construction of system equals the reduction of energy consumption due to system operation. It can be expressed as follows (Huang *et al.*, 2012): $$T_{energy} = \frac{Q_l}{Q_o}$$ Where T_{energy}(Y) is payback time of energy Q_l (J) is energy consumption due to construction of system Q_o(J) is annual reduction of energy consumption due to system operation.
En12	**Reduction of electrical peak demand (%)** Percentage of reduction in electrical peak demand.
En13	**Reduction of peak cooling load (%)** Percentage of reduction in peak cooling load.

Table within En7:

Emission Class	Houses in Ankara kgCO_2/m^2-year	Houses in Istanbul kgCO_2/m^2-year	Houses in Izmir kgCO_2/m^2-year
A	GEP<19	GEP<16	GEP<11
B	19 ≤GEP< 38	16 ≤GEP< 32	11 ≤GEP< 22
C	38 ≤GEP<47	32 ≤GEP< 40	22 ≤GEP< 28
D	47 ≤GEP< 56	40 ≤GEP< 48	28 ≤GEP< 34
E	56 ≤GEP< 66	48 ≤GEP< 56	34 ≤GEP< 39
F	66 ≤GEP< 82	56 ≤GEP< 70	39 ≤GEP< 49
G	82 ≤GEP	70 ≤GEP	49 ≤GEP

<table>
<tr><td>En14</td><td>Electricity consumption per year (kWh/year)

Annual electricity consumption of the buildings after undertaking retrofit.</td></tr>
<tr><td>En15</td><td>Normalized energy consumption (kWh/m^2 year or kWh/m^2 month)

Total energy consumption per meter square per a specific time of a building before undertaking retrofit.</td></tr>
<tr><td>En16</td><td>Energy consumption class

An example for classifying the Energy Performance (EP) for single family houses in Ankara, Istanbul and Izmir is illustrated as follows (Gugul et al., 2018):

<table>
<tr><th>Energy Class</th><th>Houses in Ankara kWh$_2$/m^2-year</th><th>Houses in Istanbul kWh$_2$/m^2-year</th><th>Houses in Izmir kWh$_2$/m^2-year</th></tr>
<tr><td>A</td><td>EP<114</td><td>EP<96</td><td>EP<66</td></tr>
<tr><td>B</td><td>114 ≤EP< 228</td><td>96 ≤EP< 192</td><td>66 ≤EP< 132</td></tr>
<tr><td>C</td><td>288 ≤EP<285</td><td>192 ≤EP<240</td><td>132 ≤EP<165</td></tr>
<tr><td>D</td><td>285 ≤EP< 342</td><td>240 ≤EP< 288</td><td>165 ≤EP< 198</td></tr>
<tr><td>E</td><td>342 ≤EP< 399</td><td>288 ≤EP< 336</td><td>198 ≤EP< 231</td></tr>
<tr><td>F</td><td>399 ≤EP< 499</td><td>336 ≤EP< 420</td><td>231 ≤EP< 289</td></tr>
<tr><td>G</td><td>499 ≤EP</td><td>420 ≤EP</td><td>289 ≤EP</td></tr>
</table></td></tr>
<tr><td>En17</td><td>Total site energy (GJ)

Total amount of energy used in site in the retrofit project.</td></tr>
<tr><td>En18</td><td>Life Cycle Analysis (LCA)

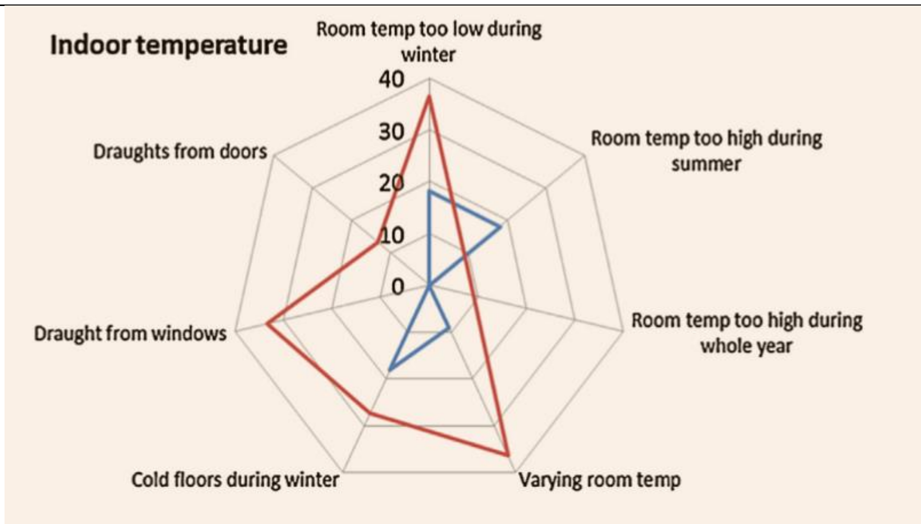
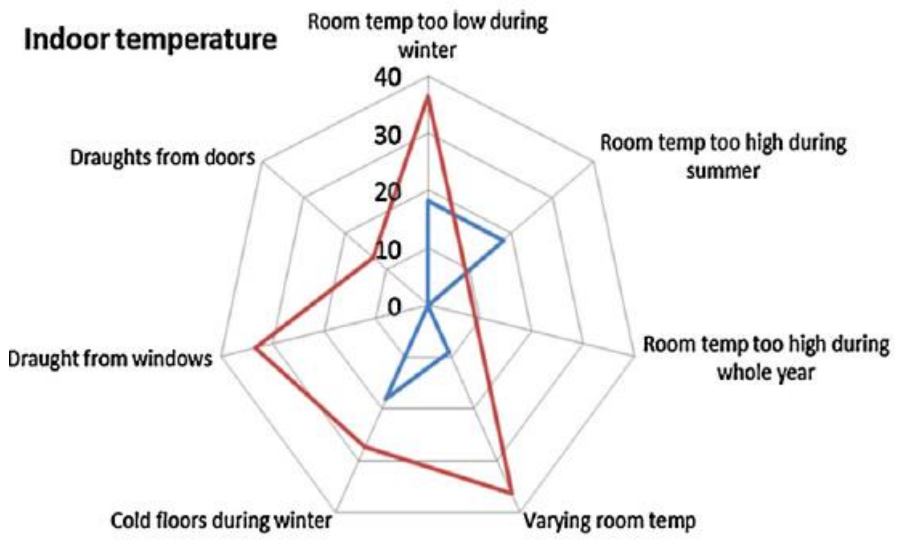
To assess the life cycle environmental impact, LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal.</td></tr>
</table>

C.) Health and Safety:

No.	Indicators
HS1	**Removal of statutory orders** Common building defects can be occurred in various forms and all types of buildings irrespective of age. The Building Department or related authorities may issue advisory, warning letters or statutory orders to building owners to investigate and rectify defects or irregularities (due to spalling concrete, defective sprinkler system, drainage repair, Legionnaire's' Disease.)
HS2	**Reduction in number of accidents per year** Reduction in the number of accidents (injuries or casualties) per year.
HS3	**Reduction in number of legal cases per year** Reduction in number of legal cases due to underperformance of facilities per year.
HS4	**Reduction in number of compensation cases per year** Reduction in number of cases (due to underperformance of facilities) where the injured parties are compensated per year.
HS5	**Reduction in amount of compensation paid per year** Reduction in number the amount of compensation paid to the injured parties (due to underperformance of facilities) per year.
HS6	**Reduction in number of health and safety complaints per year** Reduction in number the health and safety complaints (due to underperformance of facilities) per year.
HS7	**Reduction in number of lost workdays per year** Reduction in number of days off (due to work-related illness/injuries arising from underperformance of facilities) per year.
HS8	**Reduction in number of incidents of specific disease per year** Reduction in number incidents of specific disease (with medical certificate) per year.

C.) Users' Perspective:

No.	Indicators
U1	**Predicted Mean Vote (PMV) index** Based on the American Society of Heating (2013), a seven-point thermal sensation scale known as PMV has the following range: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly neutral), -2 (cool) and -3 (cold). The PMV equation is a function of environmental variables as: $$PMV = f\,(t_a, t_{mrt}, v, p_a, M, I_{cl})$$ where t_a is air temperature (°C) t_{mrt} is mean radiant temperature (°C) v is relative air velocity (m/s) p_a is humidity (vapour pressure) (kPa) M is metabolic rate (W/m^2) I_{cl} is clothing insulation (clo). From ISO7730, standard and acceptable indoor climate with: PMV: -0.5 - + 0.5; PPD < 10%
U2	**Predicted Percentage of Dissatisfied (PPD) (%)** Based on Fanger (1970) developed empirical relationship of PMV with the PPD, it predicts the percentage of people who feel more than slightly warm or cool, where the relationship is represented as: $$PPD = 100 - 95\exp\,(-0.03353 \text{ X } PMV^4 - 0.219\text{X } PMV^2)$$
U3	**Indoor air temperature (°C)** The maximum acceptable indoor temperature is calculated according to EN15251 adaptive comfort model as (Gourlis and Kovacic, 2016): $$T_{max} = 0.33\ T_{rm} + 22.8$$ From Zuhaib *et al* (2018), it used Testo-480 portable measuring instruments to measure the temperature, where measurement probes were placed 1.0 m above the floor near the respondents during normal working hours, based on a Class II field research protocol. From Jankovic (2019), it measures the frequency of occurrence internal air temperatures less than or equal to 21 °C was calculated before and after the retrofit. From Liu et. al (2015), the percentage of complaints before and after retrofit is as follows:

	 (red: before retrofit; blue: after retrofit)
U4	**Discomfort hours in summer (%)** It calculated the percentage of hours when operative temperature is > 26 °C (Liu *el al.*, 2015). Annual discomfort rates % can also be calculated by using the annually, weekly and daily indoor air temperature profiles (Silvero *et al.*, 2019). They are modelled hourly for the thermal zone presenting the worse thermal performance and, the percentage of the simulated time in which the operative temperatures exceed 27°C or the value recommended by the EN 15251 for buildings in the Category II, corresponds to the overheating rate. Another diagram for discomfort parameters regarding indoor temperature is as follows: (Liu *el al.*, 2015) (red: before retrofit; blue: after retrofit): 

U5 **Thermal Comfort Level**

The indoor environment is divided into different levels such as “Best”, “Good”, “Acceptable” and “Unacceptable” according to Swedish standards.

Class	PPD	PMV
Best	<6%	+-0.2
Good	<10%	+-0.5
Acceptable	<15%	+.0.7
Unacceptable	>15%	<-0.7 or >0.7

U6 **Ventilation and infiltration rates (h^{-1})**

The air change rate A_s can be calculated based on the average CO_2 generation rate (Liu *el al*., 2015):

$$A_s = \frac{6x10^4 nC_p}{V(C_s - C_R)}$$

where

A_s: air change rate (h^{-1}); N: number of people in space

C_p: average CO_2 generation rate per person; V: volume of the room (m^3)

C_s: steady state indoor CO_2 concentration (ppm)

C_r: CO_2 concentration in supply air (ppm)

The infiltration rate (f_v) can be calculated as:

$$f_v = \frac{1}{t} ln \frac{C_{ia} - C_{st}}{C_{ib} - C_{st}}$$

where

f_v: fresh air ventilation rate through infiltration (1/s)

C_{ia}: CO_2 concentration at moment a (mg/m^3)

C_{ib}: CO_2 concentration at moment b (mg/m^3)

C_{st}: CO_2 concentration in supply air at time t (s) over which the ventilation rate is calculated.

U7 **Indoor CO_2 levels (ppm)/other harmful substances (before retrofit)**

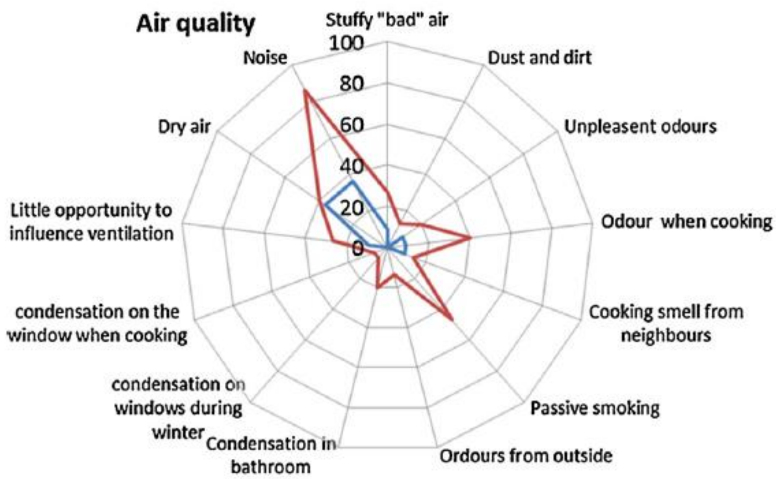
From Zuhaib *et. al* (2018), the CO_2 generated by the occupants is used as a tracer gas. The steady state method is used where CO_2 concentration has reached equilibrium represented by a constant level of concentration over a time period of 10-20 min.

From Silva *et. al*., (2013), the equipment used are as follows: Testo 435 to measure the level of CO_2 and CO (ppm); TSI DustTrack II to measure PM_{10} (mg/m^3); ZDL-300 to measure HCHO (ppm); ZDL-1200 to measure O_3 (ppm); and Photovac 2020 ppb to measure VOC (ppb/ppm).

<table>
<tr>
<td>U8</td>
<td>

Internal air quality

From Hall *et al.* (2013), the mould growth potential (mm) and indoor RH fluctuation (%) were studied. Air quality diagram with various factors and respective % of complaints are illustrated (Liu *et al*., 2015): (red: before retrofit; blue: after retrofit)



</td>
</tr>
<tr>
<td>U9</td>
<td>

Work productivity

It can be reflected by (1) active days gained from reducing sick days and (2) healthy life year loss.

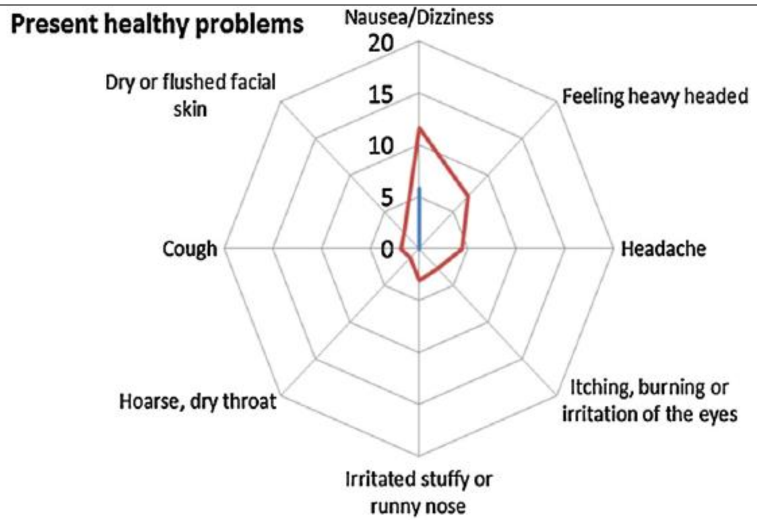
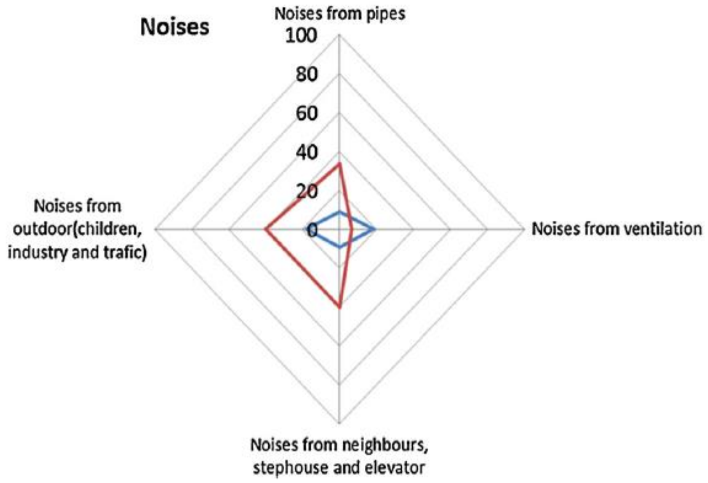
(1) Sick day is linear combination of absenteeism (due to building-related illness) and presenteeism (working with illness) (Bleyl *et al*., 2019).

(2) Healthy life years
Many building-related illnesses affects the mortality but it cannot be measured through sick days. Hence, the disability adjusted life year (DALY) indicator is used to estimate both mortality and morbidity along with sick days indicator for a complete understanding of severity of indoor exposure (Bleyl *et al*., 2019).

From World Health Organization (2019): DALY = YLL + YLD

Where
YLL: Years of Life Lost due to premature mortality in the population
YLD: Years Lost due to Disability for people living with the health condition or its consequences.
Present healthy problems diagram with various factors and respective % of complaints are shown as follows (Liu *et al*., 2015):

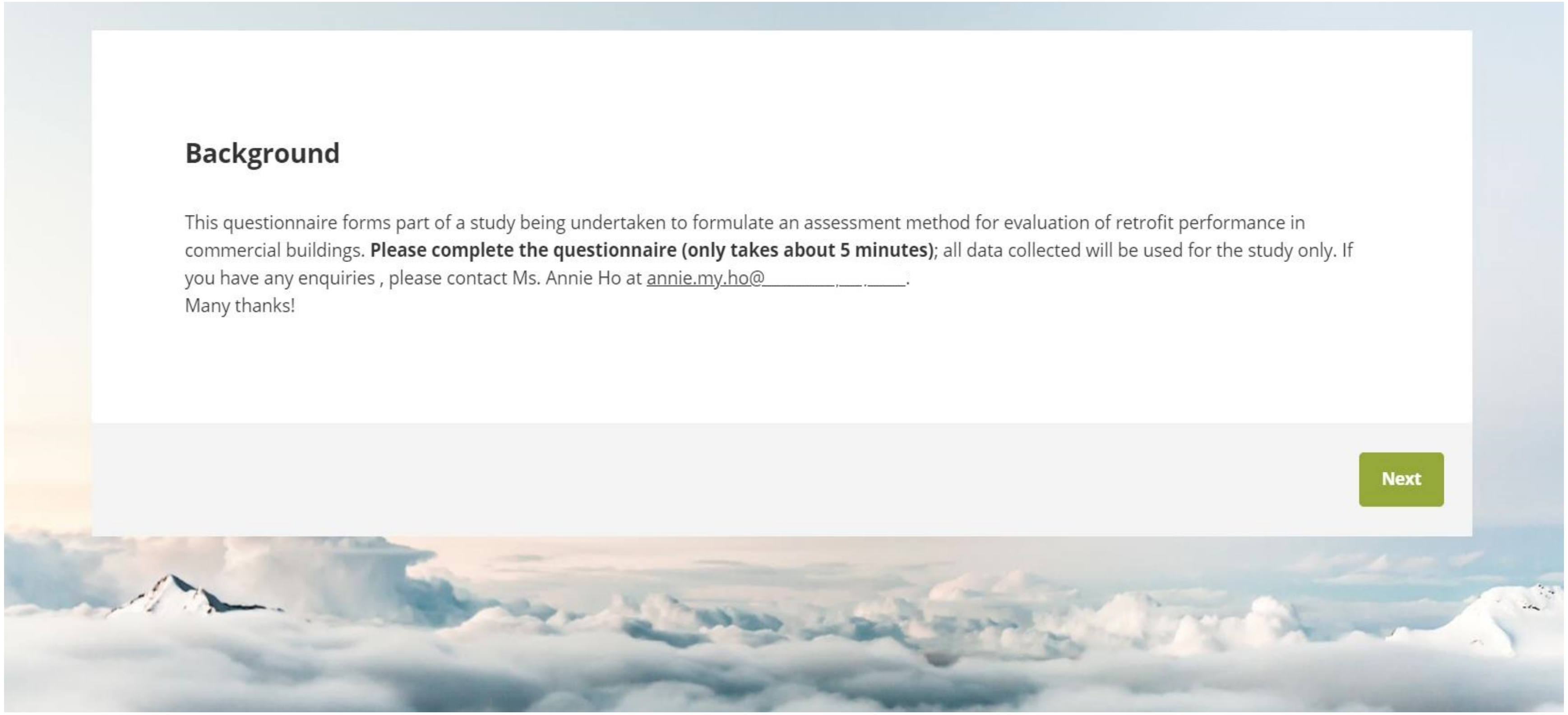
</td>
</tr>
</table>

	 (red: before retrofit; blue: after retrofit)
U10	**Workforce performance (€/m²)** From Bleyl *et al*. (2019), an online survey tool “Comfortmeter” is used to objectify the subjective comfort experience of building users, where the survey polls on 6 aspects of comfort (thermal comfort, air quality, acoustics, lighting, individual control and office environment and cleanliness) on the work performance impact. The comfort scores of building which are benchmarked against similar buildings in the Comfortmeter database.
U11	**Visual comfort – workplane illuminance (lux)** It may refer to the recommended minimum workplace illuminance given in EN15251 for typical occupancy zones (Zuhaib *et al*, 2018).
U12	**Acoustic comfort – Nosie level (Leq - equivalent continuous weighted sound pressure level (dBA))** The Leq value was set by averaging the sound pressure levels for 2 hours and then defining the average as a representative value on a 2-hour basis (Zuhaib *et al*, 2018). Noise diagram with various factors and respective % of complaints are as follows: (Liu *et al*., 2015):  (red: before retrofit; blue: after retrofit)

Appendix B.

Online Survey

Layout of the online questionnaire displayed on computer screen



Section 1. Personal particulars (please tick/fill in the box/space below)

1.1 Gender *

◯ Male

◯ Female

1.2 Working experience in the building industry *

years

1.3 Employer *

◯ Government

◯ Non-government public organization

◯ Private company

1.4 Role of current employer *

◯ Owner/developer

◯ Management company

◯ Contractor

◯ Others (please specify)

1.5 Job level *

◯ Strategic level (e.g. director, department head, chief engineer)

◯ Tactical level (e.g. manager, engineer)

◯ Others (please specify)

1.6 Buildings / premises that you have worked on (*indicate all that apply*) *

- [ ] Office
- [ ] Retail
- [ ] Hotel
- [ ] Others (please specify)

1.7 Professional member (Corporate class or above) of (*indicate all that apply*) *

- [ ] BSOMES
- [ ] HKIE
- [ ] CIBSE
- [ ] HKIFM
- [ ] Others (Please specify)

1.8 Highest academic qualification *

- ○ Associate degree / diploma / certificate
- ○ Bachelor degree
- ○ Master degree
- ○ Doctorate degree
- ○ Others (please specify)

Back Next

Section 2. Importance level of indicators

Please indicate the importance level of each indicator below (Total 19 KPIs) for evaluating the performance of retrofit projects in commercial buildings. (Level: 1 = Very low; 2 = Low; 3 = Moderate; 4 = High; 5 = Very high) *

A. Environmental Indicators

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
1. Energy savings (%) [Amount of energy saved as a result of the retrofit project.]	○	○	○	○	○
2. Normalized energy savings (kWh/sq.m year) [Amount of energy saved per square meter per year as a result of the retrofit project.]	○	○	○	○	○
3. Electricity consumption saving per year (kWh/year) [Saving in electricity consumption per year as a result of the retrofit project.]	○	○	○	○	○
4. Energy payback period (year) [Period over which the retrofitted system produces energy to recover the energy used to produce the system initially.]	○	○	○	○	○
5. Target green building label [Target green building certificate (BEAM Plus) obtained as a result of the retrofit project.]	○	○	○	○	○

Back Next

Section 2. Importance level of indicators

Please indicate the importance level of each indicator below (Total 19 KPIs) for evaluating the performance of retrofit projects in commercial buildings. (Level: 1 = Very low; 2 = Low; 3 = Moderate; 4 = High; 5 = Very high) *

B. Economic Indicators

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
6. Payback Period (year) [Time required to recover the project investment by project profits.]	○	○	○	○	○
7. Return on Investment (%) [Ratio between net profit and cost of the retrofit project.]	○	○	○	○	○
8. Internal rate of return (%) [Interest rate at which the net present value of all the cash flows from the retrofit project equal zero.]	○	○	○	○	○
9. Investment cost ($) [Total amount of money spent for the retrofit project.]	○	○	○	○	○
10. Normalized investment cost ($ /sq.m) [Total amount of money spent for the retrofit project per square meter.]	○	○	○	○	○
11. Life Cycle Cost ($) [Sum of all recurring and one-time costs of the retrofit project over the full life span.]	○	○	○	○	○
12. Increase of building value (%) [Percentage of increase in building value as a result of the retrofit project.]	○	○	○	○	○

Section 2. Importance level of indicators

Please indicate the importance level of each indicator below (Total 19 KPIs) for evaluating the performance of retrofit projects in commercial buildings. (Level: 1 = Very low; 2 = Low; 3 = Moderate; 4 = High; 5 = Very high) *

C. Health and Safety

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
13. Ratio of actual to target no. of statutory orders removed (%) [Fulfillment of the target level in removal of statutory orders over a certain period.]					
14. Ratio of actual to target no. of accidents per year reduced (%) [Fulfillment of the target level in reduction of number of accidents over a certain period.]					

D. Users' Perspective *

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
15. Target indoor air temperature (%) [Fulfillment of the target indoor air temperature.]					
16. Δ Indoor carbon dioxide levels or harmful substances (ppm) [Reduction in concentration of carbon dioxide or harmful substances as a result of the retrofit project.]					

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
substances as a result of the retrofit project.]					
17. Target IAQ class [Target (Good/Excellent) Class of the Environmental Protection Department's IAQ Certification Scheme obtained as a result of the retrofit project.]	○	○	○	○	○
18. Target work plane illuminance (lux) [Fulfillment of the target work plane illuminance.]	○	○	○	○	○
19. Target indoor equivalent continuous weighted sound pressure level (dBA) [Fulfillment of the target indoor average sound pressure level.]	○	○	○	○	○

Section 3. Comments/suggestions

Please state below if you have any comments/suggestions: (Optional)

--- End ---

Thank you very much!

Back

Finish

Appendix C.

Introduction video for the interviews

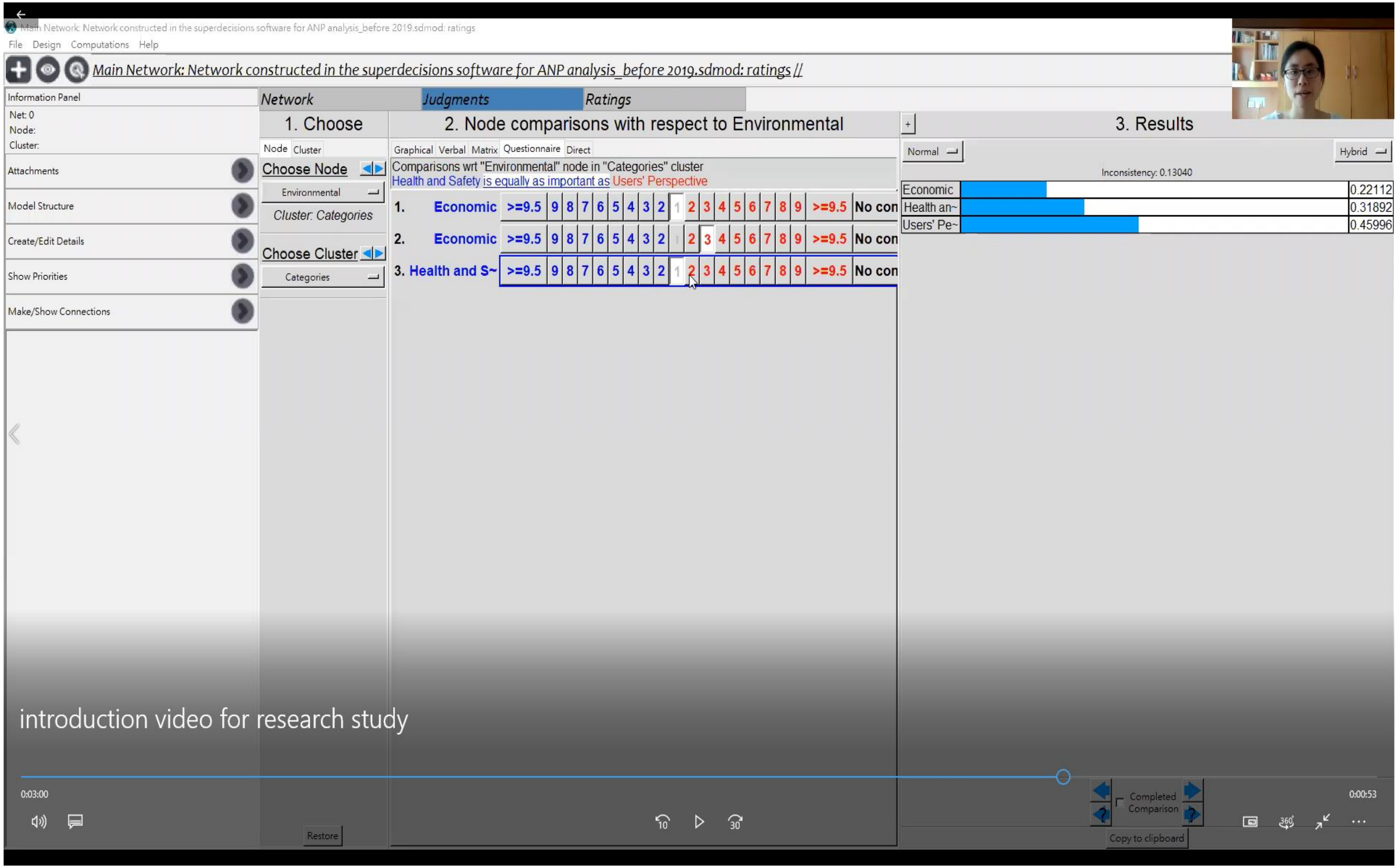


Figure C. Four minutes introduction video before carrying out interview

Appendix D.

Evaluation form for in-depth interviews

Introduction for Interview:

Before the interview

- **Part 1 (~ 30minutes):**

  Objective:

  Find out the retrofit measures adopted in the building being evaluated.

  Instruction:

  Please fill in the information about building being evaluated (e.g. age of the building, no. of storeys, gross floor area, type of retrofit measures etc.).

During interview:

- **Part 2 (~1 hours):**

  Objective:

  Find out the importance weights of KPIs by conducting a series of pairwise comparisons (with rating scale 1-9).

  Instruction:

  There are total 8 key performance indicators (KPIs) (27 pairs of comparisons).

  For each pairwise comparison, the interviewees could enter the absolute numbers (1 to 9) of the fundamental scale in the software programme.

  Remarks:

  1. The consistency ratio (CR) needs to be <0.05 for 3x3 matrix.
  2. For *CR >0.05*, the interviewee will be asked to consider changing his judgment to a plausible value in range such that the inconsistency could be improved.

Part 1. Assessing the performance of retrofit projects in commercial buildings (SAMPLE)

This evaluation form comprises 1 section. It related to information about building being evaluated.

Information about building being evaluated

1.1 **Name of the building**

___ABC Centre (Optional)__________

1.2 **Types of premises in the building**

☑ Office ☑ Retail ☐ Hotel

☐ Others (please specify: ___________________________)

1.3 **Age of the building**

____36______ year(s)

1.4 **Number of storeys in the building**

No. of floors	**Type**			
	Office	Retail	Carpark	Total
	26	2	-	28

1.5 **Total Gross floor area (GFA)**

___5990_____ m^2

1.6 **Internal floor area (IFA)**

___65800 (overall)__ m^2

Project description

1.7 Project duration

Retrofit measures	Start date	End date	Cost/breakdown
1. Replace with energy efficient lamp	Jan 2016	Dec 2017	$100,000
2. Replacement work of chiller water pipe	March 2016	April 2016	$220,000
3. Replacement of a new fire sprinkler systems	Oct 2016	April 2016	$80,000

1.8 Project cost

$400,000

1.9 Other project description

--- End of Part 1---

Part 2. Assessing the performance of retrofit projects in commercial buildings (SAMPLE)

This evaluation form comprises 2 sections. Part 2A contains personal particulars of the interviewee. Part 2B solicits the importance weights of key performance indicators (KPIs) under this assessment method by conducting a series of pairwise comparisons through analytic network process (ANP).

Part 2A: Personal particulars (please tick/fill in the box/space below)

1.1 **Date**

__3/6/2020___

1.2 **Work experience in the building industry**

___25_______ years

1.3 **Employer**

☐ Government ☐ Non-government public organization

☑ Private company

1.4 **Job title**

Senior Manager____________

1.5 **Buildings / premises that you have worked on (*indicate all that apply*)**

☑ Office ☑ Retail ☑ Hotel

☐ Others (please specify: ______________________________)

1.6 **Professional member (Corporate class or above) of: (*indicate all that apply*)**

☑ BSOMES ☑ HKIE ☑ CIBSE ☑ HKIFM

☐ Others (please specify: ________________________________)

1.7 **Highest academic qualification**

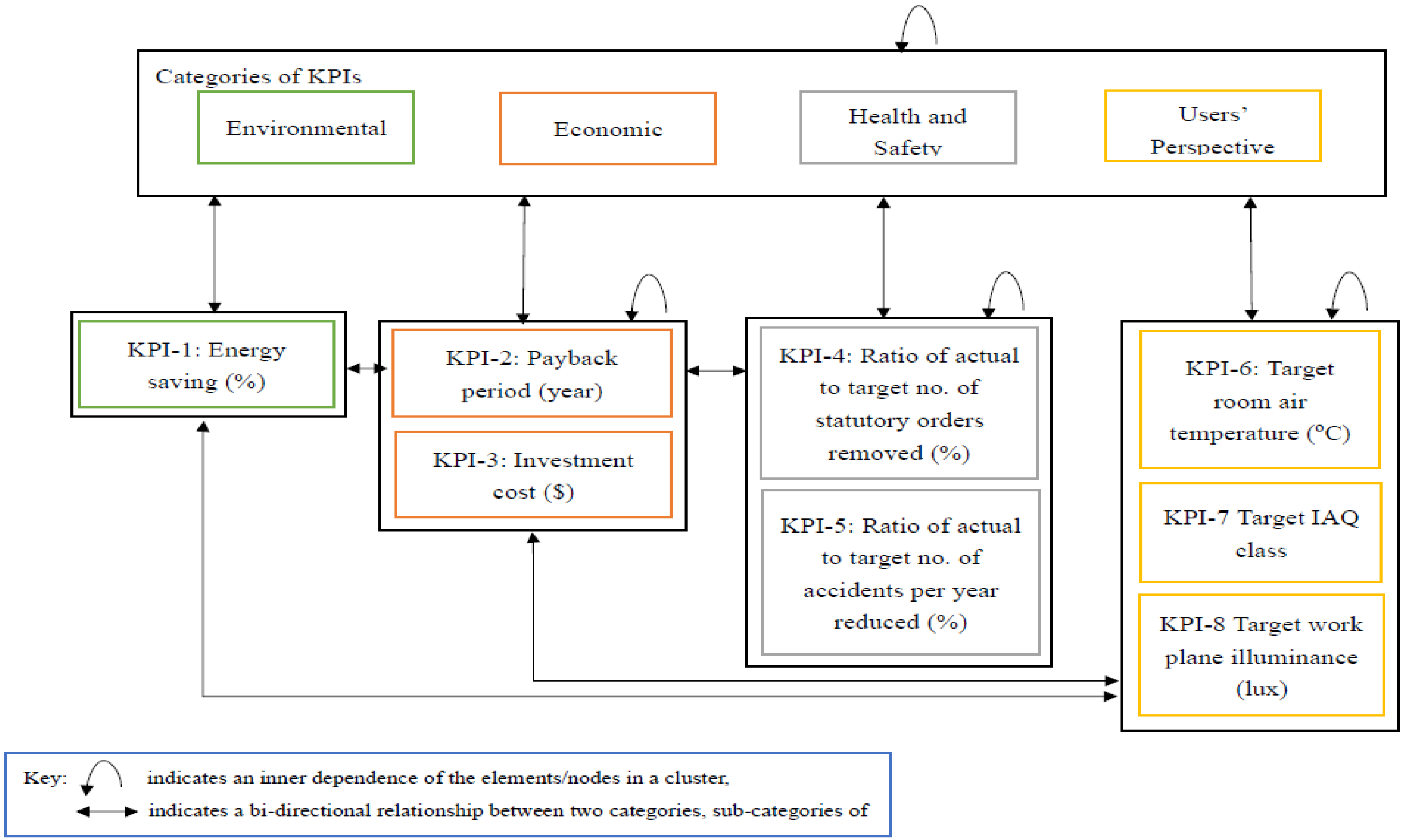
☐ Associate degree / diploma / certificate ☐ Bachelor degree

☑ Master degree ☐ Doctorate degree

☐ Others (please specify: ________________________________)

Part 2B – Pairwise comparisons by analytic network process (ANP)

The ANP networks for the four aspects and inter-relationship diagram is shown below.



igure 1. ANP network constructed for analysis (for building retrofitting carried out before 2019)

The importance weights of key performance indicators (KPIs) under this assessment method can be solicited by conducting a series of pairwise comparisons through analytic network process (ANP). (where *“1” = “Equal importance”, “3”= “Moderate importance”, “5”= Strong importance, “7” = “Very strong importance”, “9= Absolute importance”, “2, 4, 6, 8” = intermediate value*)

Comparisons with respect to “Environmental” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Health and Safety	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Economic” node in “Categories” cluster		
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Health and Safety	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Health and Safety” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environmental
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Users’ Perspective

Comparisons with respect to “Users’ Perspective” node in “Categories” cluster		
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Environmental
Economic	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety
Environmental	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Health and Safety

Comparisons with respect to “Economic” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster		
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)

Comparisons with respect to “Users’ Perspective” node in “Categories” cluster		
KPI-6: Target indoor air temperature (°C)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (°C)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster		
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)

Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster		
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)

Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster		
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-7: Target IAQ class
KPI-6: Target indoor air temperature (ºC)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)
KPI-7: Target IAQ class	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-8: Target workplane illuminance (lux)

Comparisons with respect to “Target indoor air temperature (ºC)” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

Comparisons with respect to “Target IAQ class” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster		
KPI-2: Payback period (year)	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	KPI-3: Investment cost ($)

---End of Part 2---

Appendix – Description of the KPIs

KPI	A) Environmental Aspects
1	Energy saving (%) [Amount of energy saved as a result of the retrofit project.]
	B) Economic Aspects
2	Payback period (year) [Time required to recover the project investment by project profits.]
3	Investment cost ($) [Total amount of money spent for the retrofit project.]
	C) Health and Safety
4	Ratio of actual to target no. of statutory orders removed (%) [Fulfillment of the target level in removal of statutory orders over a certain period.]
5	Ratio of actual to target no. of accidents per year reduced (%) [Fulfillment of the target level in reduction of number of accidents over a certain period.]
	D) Users' Perspective
6	Target indoor air temperature (^{o}C) [Fulfillment of the target indoor air temperature.]
7	Target IAQ class [Target (Good/Excellent) Class of the Environmental Protection Department's IAQ Certification Scheme obtained as a result of the retrofit project.]
8	Target workplane illuminance (lux) [Fulfillment of the target workplane illuminance.]

- **<u>Part 3 (After interview):</u>**

Objective:

Study the building retrofit performance of the evaluated building.

<u>Instruction:</u>

The interviewees could evaluate the performance of building in various aspect by five-point scale. Please also include reasons, supportive data and other relevant information.

Remarks:

The importance weighting of KPIs depends on the result in part 2.

Part 3 – Building retrofit performance of building being evaluated (SAMPLE)

This evaluation form comprises 1 section. It studies the building retrofit performance of building being evaluated.

A.) Please ☑ **tick the appropriate boxes** (Yes or No) to indicate whether the indicators applicable to the project.

B.) If "Yes", please write down the **actual values of the indicators (e.g. achieved/target/Δ).**

C.) Please circle a number **(1-5)** that represents the **performance score of each listed indicator for evaluating the commercial buildings being evaluated** (where *"1" = Very poor, "2" = Poor, "3" = Fair, "4" = Good, "5" = Very good*).

D.) Please also provide the **reasons, supportive data and other information** to assist the rating process (if appliable).

Key performance indicators (KPIs) No.	Indicator	Applicable to the project?	Actual values of the KPI (e.g. achieved/target/Δ)	Performance Scores	Reasons, supportive data & other information
A) Environmental Aspects					
1	Energy saving (%) [Amount of energy saved as a result of the retrofit project.]	☑ Yes ☐No	Δ= (6293100-5831600) kWh/6293100kWh = 7.33%	1 2 3 4 5	Electricity consumption per total area was reduced from 121kWh/m^2 to 112 kWh/m^2.
B) Economic Aspects					
2	Payback period (year) [Time required to recover the project investment by project profits.]	☑ Yes ☐No	The actual simple payback for LED retrofit: 6 years; HVAC retrofit: 8 years Fire sprinkler systems: -	1 2 3 4 5	For LED retrofit, the calculation takes into consideration equipment costs, labor costs, and electricity costs. For HVAC retrofit, it has 2 to 5 years payback expectation based on an initial energy audit.
3	Investment cost ($) [Total amount of money spent for the retrofit project.]	☑ Yes ☐No	Total investment cost: $400,000 Target investment cost: $ 380,000 Δ = +5.26% (over budget)	1 2 3 4 5	To incorporating many other sustainability performance features necessary to achieve a better rating in BEAM Plus, it is acceptable for a small range of over budget.

Key performance indicators (KPIs)		Applicable to the project?	Actual values of the KPI (e.g. achieved/target/Δ)	Performance Scores	Reasons, supportive data & other information
No.	**Indicator**				
C) Health and Safety					
4	Ratio of actual to target no. of statutory orders removed (%) [Fulfillment of the target level in removal of statutory orders over a certain period.]	☑ Yes ☐No	Achieved and Target = 2 orders (100% Fulfil the target)	1 2 3 4 5	Statutory order regarding to fire safety components and unauthorized building works was removed.
5	Ratio of actual to target no. of accidents per year reduced (%) [Fulfillment of the target level in reduction of number of accidents over a certain period.]	☑ Yes ☐No	Achieved and Target = 1 person (100% Fulfil the target; people are now free from Legionnaires' disease)	1 2 3 4 5	From record, fewer people took sick leave as well after retrofit (e.g. reduction of air pollutants due to HVAC retrofit).
D) Users' Perspective					
6	Target indoor air temperature (ºC) [Fulfillment of the target indoor air temperature.]	☑ Yes ☐No	Target: 23.5ºC; Achieved: 23.5ºC (>80% frequency) Δ: 100% Fulfil the target	1 2 3 4 5	In most of the time, office area can achieve target air temperature (23.5ºC) during office hours.
7	Target IAQ class [Target (Good/Excellent) Class of the Environmental Protection Department's IAQ Certification Scheme obtained as a result of the retrofit project.]	☑ Yes ☐No	Achieved and Target = Good Class (100% Fulfil the target)	1 2 3 4 5	Good Class certificate for IAQ was issued by the EPD in 2017-2018. (Retrofit done in late 2016)
8	Target workplane illuminance (lux) [Fulfillment of the target workplane illuminance.]	☑ Yes ☐No	Achieved and Target = average 500 lux (100% Fulfil the target)	1 2 3 4 5	The occupants reflected that the visual comfort was highly improved. They can now work more efficiently.

--- End of Part 3---

- **Other supportive data for the evaluation (Building B8)**

For B8: Replacement of 1 x 1150 TR Chiller and 2 x 575 TR Oil Free Chiller

Chiller plant has been put into operation over 20 years. There are totally five sets of indirect sea water cooled centrifugal chillers serving two office buildings, Tower 1 and Tower 2. The building is always seeking all possibilities of reducing electricity consumption for conservation the environment. As a result, 1 set of 1,150 Refrigeration Ton (RT) and 2 set of 575 RT lower voltage (LV) chillers had been replaced with environment-friendly refrigerant HFC-R134a instead of R-22.

Reviewing the chiller log, variable speed drive (VSD) which was adopted for both new Chillers to improve the efficiency during part load operations. In addition, the new technology of permanent magnet motor (oil free) with active magnetic bearing is used on the 575 RT chiller. The advantage of this technology is low noise and vibration; elimination of oil tank and lubrication piping due to lubricating oil free; high performance; compact and light in weight as a direct connection between compressor and motor and maintenance cost saving.

Figure 1 New 1,150 TR Chiller #3

Figure 2 New 575 TR Chiller #4

Figure 3 New 1,150 TR Chiller #5

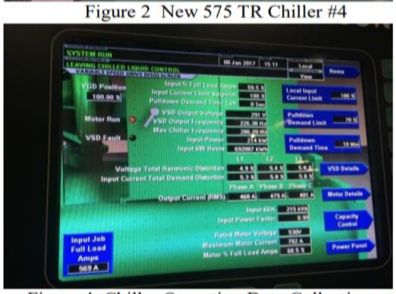


Figure 4 Chiller Operation Data Collection and Logging

Figure D.1 Replacement of chillers in B8

Chiller Replacement Completion
Chiller No.1: Nov-17 *(Comparison Period: Jan~Nov 2016 vs 2018)*
Chiller No.2: Jan-18

Account No.: 10571-03108-4
Meter No.: 9063015
Equipment: Chiller No.1

	Electricity Consumption (kWh)	
	2016	2018
Jan	70,022	76,714
Feb	35,224	30,266
Mar	71,402	70,957
Apr	69,471	64,207
May	151,261	132,201
Jun	153,632	137,799
Jul	123,809	176,585
Aug	178,123	192,873
Sep	132,625	162,524
Oct	146,218	105,599
Nov	112,612	47,874
Total	**1,244,399**	**1,197,599**
Difference		(46,800)

Account No.: 10571-03108-4
Meter No.: 9074752
Equipment: Chiller No.2

	Electricity Consumption (kWh)	
	2016	2018
Jan	61,690	21,504
Feb	21,037	19,532
Mar	29,554	55,214
Apr	201,500	62,431
May	182,459	118,616
Jun	112,286	148,081
Jul	131,660	9,901
Aug	229,722	2,000
Sep	170,835	40,276
Oct	111,720	116,449
Nov	86,891	86,737
Total	**1,339,354**	**680,741**
Difference		(658,613)

Account No.: 10571-03108-4
Meter No.: 9074726
Equipment: Chiller No.3

	Electricity Consumption (kWh)	
	2016	2018
Jan	38,054	9,917
Feb	51,765	16,587
Mar	64,855	35,573
Apr	2,848	29,531
May	86,940	91,716
Jun	202,331	78,551
Jul	189,863	142,525
Aug	57,963	163,399
Sep	134,991	100,454
Oct	158,077	11,730
Nov	148,520	42,218
Total	**1,136,207**	**722,201**
Difference		(414,006)

Account No.: 10571-03108-4
Meter No.: 9094295
Equipment: Chiller No.4

	Electricity Consumption (kWh)	
	2016	2018
Jan	107,573	121,608
Feb	83,297	106,408
Mar	84,615	138,164
Apr	75,329	90,714
May	89,391	186,862
Jun	252,014	103,633
Jul	279,965	224,744
Aug	269,368	260,306
Sep	252,374	169,342
Oct	188,353	92,721
Nov	174,242	127,858
Total	**1,856,521**	**1,622,360**
Difference		(234,161)

Account No.: 10571-03108-4
Meter No.: 9062992
Equipment: Chiller No.5

	Electricity Consumption (kWh)	
	2016	2018
Jan	193,895	125,948
Feb	169,833	105,647
Mar	203,825	140,532
Apr	287,793	249,508
May	257,384	146,952
Jun	165,699	293,137
Jul	149,909	188,036
Aug	147,679	141,876
Sep	145,704	207,764
Oct	178,098	252,320
Nov	129,827	228,140
Total	**2,029,646**	**2,079,860**
Difference		50,214

Electricity Consumption for Gateway I Chiller Plant

	Electricity Consumption (kWh)	
	2016	2018
Jan	471,234	355,691
Feb	361,156	278,440
Mar	454,251	440,440
Apr	636,941	496,391
May	767,435	676,347
Jun	885,962	761,201
Jul	875,206	741,791
Aug	882,855	760,454
Sep	836,529	680,360
Oct	782,466	578,819
Nov	652,092	532,827
Total	**7,606,127**	**6,302,761**
Difference		(1,303,366)

Figure D.2 Details of electricity consumption in B8 before and after retrofit

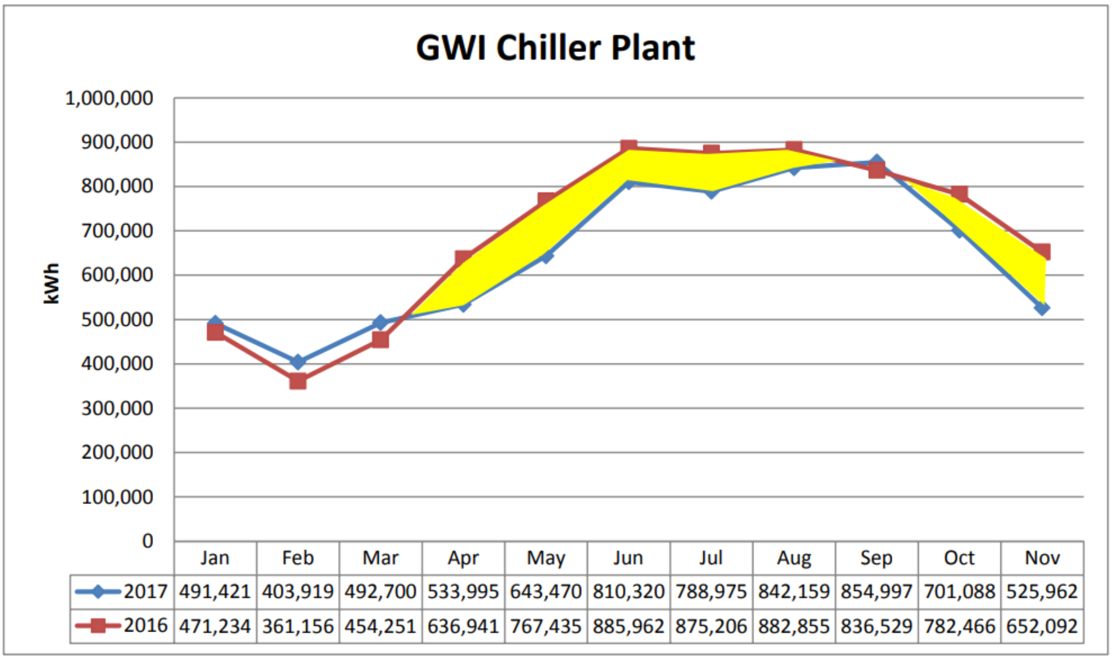


Figure D.3 Electricity consumption in B8 before and after retrofit

Figure 7.3 shows the electricity consumption record of chiller plant in 2016 and 2017 (up to Nov) The power consumption of the entire chiller plant in year 2016 and year 2017 (up to Nov) are 7,606,127 kWh and 7,089,006 kWh respectively. The accumulative energy saving after upgrading works is 517,121kWh.

Appendix E.

Results of interviews -

Pairwise comparisons in ANP

Appendix E: Decisions of the interviewees in pairwise comparisons in ANP

Interviewee #1

For categories:

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	1/5	1/3	0.10473
Health and Safety	5	1	3	0.63699
Users' Perspective	3	1/3	1	0.25829
			Consistency ratio	0.03703

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	2	1/3	0.23849
Health and Safety	1/2	1	1/4	0.13650
Users' Perspective	3	4	1	0.62501
			Consistency ratio	0.01759

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	2	3	0.23849
Environmental	1/2	1	1/4	0.13650
Users' Perspective	1/3	4	1	0.62501
			Consistency ratio	0.01759

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	1	1/5	0.15618
Environmental	1	1	1/3	0.18517
Health and Safety	5	3	1	0.65864
			Consistency ratio	0.02795

For the four aspects:

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/6	0.14286
KPI-3: Investment Cost ($)	6	1	0.85714
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	4	0.80000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/4	1	0.20000
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (ºC)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (ºC)	1	4	6	0.790097
KPI-7: Target IAQ class	1/4	1	2	0.19288
KPI-8: Target workplane illuminance (lux)	1/6	1/2	1	0.10615
			Consistency ratio	0.00885

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	4	0.80000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/4	1	0.20000
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/5	2	0.17212
KPI-7: Target IAQ class	5	1	6	0.72585
KPI-8: Target workplane illuminance (lux)	1/2	1/6	1	0.10203
			Consistency ratio	0.02795

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	3	4	0.62501
KPI-7: Target IAQ class	1/3	1	2	0.23849
KPI-8: Target workplane illuminance (lux)	1/4	1/2	1	0.13650
			Consistency ratio	0.01759

(k) Comparisons with respect to "Target indoor air temperature (^{o}C)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/6	0.14286
KPI-3: Investment Cost ($)	6	1	0.85714
		Consistency ratio	0.00000

(l) Comparisons with respect to "Target IAQ class" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/3	0.25000
KPI-3: Investment Cost ($)	3	1	0.75000
		Consistency ratio	0.00000

(m) Comparisons with respect to "Target workplane illuminance (lux)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

<u>Interviewee #2</u>

<u>For categories:</u>

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	1/3	3	0.24264
Health and Safety	3	1	7	0.66942
Users’ Perspective	1/3	1/7	1	0.08795
			Consistency ratio	0.00675

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	1/3	1/3	0.24986
Health and Safety	3	1	6	0.65481
Users’ Perspective	3	1/6	1	0.09534
			Consistency ratio	0.01759

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	1/7	1/5	0.07506
Environmental	7	1	2	0.59173
Users’ Perspective	5	1/2	1	0.33322
			Consistency ratio	0.01361

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	8	6	0.76924
Environmental	1/8	1	1/2	0.08400
Health and Safety	1/6	2	1	0.14676
			Consistency ratio	0.01759

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/6	0.14286
KPI-3: Investment Cost ($)	6	1	0.85714
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	4	0.80000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/4	1	0.20000
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (ºC)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (ºC)	1	7	4	0.70494
KPI-7: Target IAQ class	1/7	1	1/3	0.08414
KPI-8: Target workplane illuminance (lux)	1/4	3	1	0.21092
			Consistency ratio	0.03112

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/8	0.11111
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	8	1	0.88889
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/7	1/3	0.08795
KPI-7: Target IAQ class	7	1	3	0.66942
KPI-8: Target workplane illuminance (lux)	3	1/3	1	0.24264
			Consistency ratio	0.00675

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	3	1/3	0.24986
KPI-7: Target IAQ class	1/3	1	1/6	0.09534
KPI-8: Target workplane illuminance (lux)	3	6	1	0.65481
			Consistency ratio	0.01759

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1	0.50000
KPI-3: Investment Cost ($)	1	1	0.50000
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1	0.50000
KPI-3: Investment Cost ($)	1	1	0.50000
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

<u>Interviewee #3</u>

<u>For categories:</u>

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	1/9	1/3	0.07042
Health and Safety	9	1	5	0.75140
Users’ Perspective	3	1/5	1	0.17818
			Consistency ratio	0.02795

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	4	3	0.62501
Health and Safety	1/4	1	1/2	0.13650
Users’ Perspective	1/3	2	1	0.23849
			Consistency ratio	0.01759

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	6	1/2	0.10203
Environmental	1/6	1	5	0.72585
Users’ Perspective	2	1/5	1	0.17212
			Consistency ratio	0.02795

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	2	1/5	0.17212
Environmental	1/2	1	1/6	0.10203
Health and Safety	5	6	1	0.72585
			Consistency ratio	0.02795

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	3	0.75000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/3	1	0.25000
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/5	3	0.18295
KPI-7: Target IAQ class	5	1	8	0.74184
KPI-8: Target workplane illuminance (lux)	1/3	1/8	1	0.07520
			Consistency ratio	0.04237

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	9	0.90000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/9	1	0.10000
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1/5	5	0.17818
KPI-7: Target IAQ class	5	1	3	0.75140
KPI-8: Target workplane illuminance (lux)	1/5	1/3	1	0.07042
			Consistency ratio	0.02795

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	5	1/2	0.32551
KPI-7: Target IAQ class	1/5	1	1/8	0.07013
KPI-8: Target workplane illuminance (lux)	2	8	1	0.60436
			Consistency ratio	0.00532

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/3	0.25000
KPI-3: Investment Cost ($)	3	1	0.75000
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

Interviewee #4

For categories:

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	1/4	3	0.21092
Health and Safety	4	1	7	0.70494
Users' Perspective	1/3	1/7	1	0.08414
			Consistency ratio	0.03112

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	1/5	1/4	0.09739
Health and Safety	5	1	2	0.56954
Users' Perspective	4	1/2	1	0.33307
			Consistency ratio	0.02365

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	3	1/4	0.21092
Environmental	1/3	1	1/7	0.08414
Users' Perspective	4	7	1	0.70494
			Consistency ratio	0.03112

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	7	4	0.70494
Environmental	1/7	1	1/3	0.08414
Health and Safety	1/4	3	1	0.21092
			Consistency ratio	0.03112

For the four aspects:

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/5	0.16667
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	5	1	0.83333
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	7	4	0.70494
KPI-7: Target IAQ class	1/7	1	1/3	0.08414
KPI-8: Target workplane illuminance (lux)	1/4	3	1	0.21092
			Consistency ratio	0.03112

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/5	0.16667
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	5	1	0.83333
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	8	5	0.74184
KPI-7: Target IAQ class	1/8	1	1/3	0.07520
KPI-8: Target workplane illuminance (lux)	1/5	3	1	0.18295
			Consistency ratio	0.04237

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	7	3	0.65863
KPI-7: Target IAQ class	1/7	1	1/4	0.07862
KPI-8: Target workplane illuminance (lux)	1/3	4	1	0.26275
			Consistency ratio	0.03112

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

<u>Interviewee #5</u>

<u>For categories:</u>

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	6	7	0.75825
Health and Safety	1/6	1	2	0.15125
Users’ Perspective	1/7	1/2	1	0.09051
			Consistency ratio	0.03112

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	1/6	1/4	0.08898
Health and Safety	6	1	2	0.58763
Users’ Perspective	4	1/2	1	0.32339
			Consistency ratio	0.00885

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	3	1/2	0.31962
Environmental	1/3	1	1/4	0.12196
Users’ Perspective	2	4	1	0.55842
			Consistency ratio	0.01759

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	4	2	0.55842
Environmental	1/4	1	1/3	0.12196
Health and Safety	1/2	3	1	0.31962
			Consistency ratio	0.01759

<u>For the four aspects:</u>

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	6	0.85714
KPI-3: Investment Cost ($)	1/6	1	0.14286
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/4	0.20000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	4	1	0.80000
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (ºC)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (ºC)	1	4	1	0.45793
KPI-7: Target IAQ class	1/4	1	1/3	0.12601
KPI-8: Target workplane illuminance (lux)	1	3	1	0.41606
			Consistency ratio	0.00885

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/4	0.20000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	4	1	0.80000
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	3	1	0.44343
KPI-7: Target IAQ class	1/3	1	1/2	0.16920
KPI-8: Target workplane illuminance (lux)	1	2	1	0.38737
			Consistency ratio	0.01759

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	6	1/4	0.70097
KPI-7: Target IAQ class	1/6	1	1/2	0.10615
KPI-8: Target workplane illuminance (lux)	1/4	2	1	0.19288
			Consistency ratio	0.00885

(k) Comparisons with respect to "Target indoor air temperature (^{o}C)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/4	0.20000
KPI-3: Investment Cost ($)	4	1	0.80000
		Consistency ratio	0.00000

(l) Comparisons with respect to "Target IAQ class" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	4	0.80000
KPI-3: Investment Cost ($)	1/4	1	0.20000
		Consistency ratio	0.00000

(m) Comparisons with respect to "Target workplane illuminance (lux)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	4	0.80000
KPI-3: Investment Cost ($)	1/4	1	0.20000
		Consistency ratio	0.00000

<u>Interviewee #6</u>

<u>For categories:</u>

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	1	1	0.33333
Health and Safety	1	1	1	0.33333
Users' Perspective	1	1	1	0.33333
			Consistency ratio	0.00000

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	1/2	6	0.34836
Health and Safety	2	1	7	0.58215
Users' Perspective	1/6	1/7	1	0.06949
			Consistency ratio	0.03112

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	1	5	0.45455
Environmental	1	1	5	0.45455
Users' Perspective	1/5	1/5	1	0.09091
			Consistency ratio	0.00000

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	1	1	0.33333
Environmental	1	1	1	0.33333
Health and Safety	1	1	1	0.33333
			Consistency ratio	0.00000

For the four aspects:

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	9	0.90000
KPI-3: Investment Cost ($)	1/9	1	0.10000
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1	0.50000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1	1	0.50000
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	6	1	0.48441
KPI-7: Target IAQ class	1/6	1	1/4	0.09242
KPI-8: Target workplane illuminance (lux)	1	4	1	0.42317
			Consistency ratio	0.01759

(h) Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1	0.50000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1	1	0.50000
		Consistency ratio	0.00000

(i) Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1	1	0.33333
KPI-7: Target IAQ class	1	1	1	0.33333
KPI-8: Target workplane illuminance (lux)	1	1	1	0.33333
			Consistency ratio	0.00000

(j) Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1	1	0.33333
KPI-7: Target IAQ class	1	1	1	0.33333
KPI-8: Target workplane illuminance (lux)	1	1	1	0.33333
			Consistency ratio	0.00000

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	7	0.87500
KPI-3: Investment Cost ($)	1/7	1	0.12500
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/7	0.12500
KPI-3: Investment Cost ($)	7	1	0.87500
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/3	0.25000
KPI-3: Investment Cost ($)	3	1	0.75000
		Consistency ratio	0.00000

Interviewee #7

For categories:

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	3	1/5	0.18295
Health and Safety	1/3	1	1/8	0.07520
Users’ Perspective	5	8	1	0.74184
			Consistency ratio	0.04237

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	4	1/4	0.21717
Health and Safety	1/4	1	1/9	0.06577
Users’ Perspective	4	9	1	0.71707
			Consistency ratio	0.03548

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	1/8	1/5	0.07013
Environmental	8	1	2	0.60436
Users’ Perspective	5	1/2	1	0.32551
			Consistency ratio	0.00532

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	3	1/5	0.18295
Environmental	1/3	1	1/8	0.07520
Health and Safety	5	8	1	0.74184
			Consistency ratio	0.04237

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	6	0.85714
KPI-3: Investment Cost ($)	1/6	1	0.14286
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	8	0.88889
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/8	1	0.11111
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	7	5	0.73959
KPI-7: Target IAQ class	1/7	1	1/2	0.09381
KPI-8: Target workplane illuminance (lux)	1/5	2	1	0.16659
			Consistency ratio	0.01361

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	7	0.88889
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/7	1	0.11111
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1	2	0.40000
KPI-7: Target IAQ class	1	1	2	0.40000
KPI-8: Target workplane illuminance (lux)	1/2	1/2	1	0.20000
			Consistency ratio	0.00000

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1/3	4	0.26275
KPI-7: Target IAQ class	3	1	7	0.65863
KPI-8: Target workplane illuminance (lux)	1/4	1/7	1	0.07862
			Consistency ratio	0.03112

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	6	0.85714
KPI-3: Investment Cost ($)	1/6	1	0.14286
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1	0.50000
KPI-3: Investment Cost ($)	1	1	0.50000
		Consistency ratio	0.00000

Interviewee #8

For categories:

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	1/5	1/3	0.10473
Health and Safety	5	1	3	0.63699
Users’ Perspective	3	1/3	1	0.25829
			Consistency ratio	0.03703

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	3	1/3	0.14286
Health and Safety	1/3	1	1	0.42857
Users’ Perspective	3	1	1	0.42857
			Consistency ratio	0.00000

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	3	1/5	0.18295
Environmental	1/3	1	1/9	0.07520
Users’ Perspective	5	9	1	0.74184
			Consistency ratio	0.04237

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	1/4	1/7	0.03112
Environmental	4	1	1/3	0.26275
Health and Safety	7	3	1	0.65863
			Consistency ratio	0.031112

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	7	0.87500
KPI-3: Investment Cost ($)	1/7	1	0.12500
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/9	0.10000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	9	1	0.90000
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	6	6	0.75000
KPI-7: Target IAQ class	1/6	1	1	0.12500
KPI-8: Target workplane illuminance (lux)	1/6	1	1	0.12500
			Consistency ratio	0.00000

(h) Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	1/6	0.14286
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	6	1	0.85714
		Consistency ratio	0.00000

(i) Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1/5	1/5	0.09091
KPI-7: Target IAQ class	5	1	1	0.45455
KPI-8: Target workplane illuminance (lux)	5	1	1	0.45455
			Consistency ratio	0.00000

(j) Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	2	1/3	0.23849
KPI-7: Target IAQ class	1/2	1	1/4	0.13650
KPI-8: Target workplane illuminance (lux)	3	4	1	0.62501
			Consistency ratio	0.01759

(k) Comparisons with respect to “Target indoor air temperature (^oC)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

Interviewee #9

For categories:

(a) Comparisons with respect to “Environmental” node in “Categories” cluster

	Economic	Health and Safety	Users’ Perspective	Priority vector
Economic	1	9	5	0.75140
Health and Safety	1/9	1	1/3	0.07042
Users’ Perspective	1/5	3	1	0.17817
			Consistency ratio	0.02795

(b) Comparisons with respect to “Economic” node in “Categories” cluster

	Environmental	Health and Safety	Users’ Perspective	Priority vector
Environmental	1	1/3	4	0.25828
Health and Safety	3	1	5	0.63699
Users’ Perspective	1/4	1/5	1	0.10473
			Consistency ratio	0.03703

(c) Comparisons with respect to “Health and Safety” node in “Categories” cluster

	Economic	Environmental	Users’ Perspective	Priority vector
Economic	1	1/7	1/5	0.07506
Environmental	7	1	2	0.59173
Users’ Perspective	5	1/2	1	0.33322
			Consistency ratio	0.01361

(d) Comparisons with respect to “Users’ Perspective” node in “Categories” cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	1/5	1/7	0.07506
Environmental	5	1	1/2	0.33322
Health and Safety	7	2	1	0.59173
			Consistency ratio	0.01361

For the four aspects:

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	5	0.83333
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/5	1	0.16667
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/3	4	0.26275
KPI-7: Target IAQ class	3	1	7	0.65863
KPI-8: Target workplane illuminance (lux)	1/4	1/7	1	0.07862
			Consistency ratio	0.03112

(h) Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	7	0.87500
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/7	1	0.12500
		Consistency ratio	0.00000

(i) Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/4	3	0.21092
KPI-7: Target IAQ class	4	1	7	0.70494
KPI-8: Target workplane illuminance (lux)	1/3	1/7	1	0.08414
			Consistency ratio	0.03112

(j) Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/3	3	0.24986
KPI-7: Target IAQ class	3	1	6	0.65481
KPI-8: Target workplane illuminance (lux)	1/3	1/6	1	0.09534
			Consistency ratio	0.01759

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1	0.50000
KPI-3: Investment Cost ($)	1	1	0.50000
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/4	0.20000
KPI-3: Investment Cost ($)	4	1	0.80000
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	3	0.75000
KPI-3: Investment Cost ($)	1/3	1	0.25000
		Consistency ratio	0.00000

Interviewee #10

For categories:

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	4	3	0.21092
Health and Safety	1/4	1	7	0.70494
Users' Perspective	1/3	1/7	1	0.08414
			Consistency ratio	0.03112

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	2	1/2	0.29696
Health and Safety	1/2	1	1/3	0.16342
Users' Perspective	2	3	1	0.53961
			Consistency ratio	0.00885

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	1/5	1/4	0.09739
Environmental	5	1	2	0.56954
Users' Perspective	4	1/2	1	0.33307
			Consistency ratio	0.02365

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	3	1/3	0.25828
Environmental	1/3	1	1/5	0.10473
Health and Safety	3	5	1	0.63699
			Consistency ratio	0.03703

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/4	0.20000
KPI-3: Investment Cost ($)	4	1	0.80000
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	4	0.80000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/4	1	0.20000
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/4	3	0.21092
KPI-7: Target IAQ class	4	1	7	0.70494
KPI-8: Target workplane illuminance (lux)	1/3	1/7	1	0.08414
			Consistency ratio	0.03112

(h) Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	3	0.75000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/3	1	0.25000
		Consistency ratio	0.00000

(i) Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^oC)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^oC)	1	1/4	3	0.03112
KPI-7: Target IAQ class	4	1	7	0.70494
KPI-8: Target workplane illuminance (lux)	1/3	1/7	1	0.08414
			Consistency ratio	0.03112

(j) Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (^oC)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^oC)	1	1/4	2	0.19288
KPI-7: Target IAQ class	4	1	6	0.70097
KPI-8: Target workplane illuminance (lux)	1/2	1/6	1	0.10615
			Consistency ratio	0.00885

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/3	0.25000
KPI-3: Investment Cost ($)	3	1	0.75000
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	4	0.80000
KPI-3: Investment Cost ($)	1/4	1	0.20000
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/4	0.20000
KPI-3: Investment Cost ($)	4	1	0.80000
		Consistency ratio	0.00000

Interviewee #11

For categories:

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	1	1	0.33333
Health and Safety	1	1	1	0.33333
Users' Perspective	1	1	1	0.33333
			Consistency ratio	0.00000

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	1	1	0.33333
Health and Safety	1	1	1	0.33333
Users' Perspective	1	1	1	0.33333
			Consistency ratio	0.00000

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	4	1/4	0.21717
Environmental	1/4	1	1/9	0.06577
Users' Perspective	4	9	1	0.71707
			Consistency ratio	0.03548

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	1	1	0.33333
Environmental	1	1	1	0.33333
Health and Safety	1	1	1	0.33333
			Consistency ratio	0.00000

For the four aspects:

(e) Comparisons with respect to "Economic" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	5	0.83333
KPI-3: Investment Cost ($)	1/5	1	0.16667
		Consistency ratio	0.00000

(f) Comparisons with respect to "Health and Safety" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	6	0.85714
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/6	1	0.14286
		Consistency ratio	0.00000

(g) Comparisons with respect to "Users' Perspective" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	1/4	1/9	0.06577
KPI-7: Target IAQ class	4	1	1/4	0.21717
KPI-8: Target workplane illuminance (lux)	9	4	1	0.71707
			Consistency ratio	0.003548

(h) Comparisons with respect to “Investment cost ($)” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	7	0.87500
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/7	1	0.12500
		Consistency ratio	0.00000

(i) Comparisons with respect to “Investment cost ($)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/4	3	0.20509
KPI-7: Target IAQ class	4	1	8	0.71665
KPI-8: Target workplane illuminance (lux)	1/3	1/8	1	0.07826
			Consistency ratio	0.01759

(j) Comparisons with respect to “Payback period (year)” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	1/3	4	0.25596
KPI-7: Target IAQ class	3	1	8	0.67079
KPI-8: Target workplane illuminance (lux)	1/4	1/8	1	0.07325
			Consistency ratio	0.00885

(k) Comparisons with respect to "Target indoor air temperature (^{o}C)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(l) Comparisons with respect to "Target IAQ class" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

(m) Comparisons with respect to "Target workplane illuminance (lux)" node in "Economic" cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/5	0.16667
KPI-3: Investment Cost ($)	5	1	0.83333
		Consistency ratio	0.00000

Interviewee #12

For categories:

(a) Comparisons with respect to "Environmental" node in "Categories" cluster

	Economic	Health and Safety	Users' Perspective	Priority vector
Economic	1	3	2	0.54995
Health and Safety	1/3	1	1	0.20984
Users' Perspective	1/2	1	1	0.24021
			Consistency ratio	0.01759

(b) Comparisons with respect to "Economic" node in "Categories" cluster

	Environmental	Health and Safety	Users' Perspective	Priority vector
Environmental	1	3	1/2	0.31962
Health and Safety	1/3	1	1/4	0.12196
Users' Perspective	1	4	1	0.55842
			Consistency ratio	0.01759

(c) Comparisons with respect to "Health and Safety" node in "Categories" cluster

	Economic	Environmental	Users' Perspective	Priority vector
Economic	1	1/2	1/2	0.20000
Environmental	2	1	1	0.40000
Users' Perspective	2	1	1	0.40000
			Consistency ratio	0.00000

(d) Comparisons with respect to "Users' Perspective" node in "Categories" cluster

	Economic	Environmental	Health and Safety	Priority vector
Economic	1	3	1	0.44343
Environmental	1/3	1	1/2	0.16920
Health and Safety	1	2	1	0.38737
			Consistency ratio	0.01759

For the four aspects:

(e) Comparisons with respect to “Economic” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

(f) Comparisons with respect to “Health and Safety” node in “Health and Safety” cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	3	0.75000
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/3	1	0.25000
		Consistency ratio	0.00000

(g) Comparisons with respect to “Users’ Perspective” node in “Users’ Perspective” cluster

	KPI-6 Target indoor air temperature (°C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (°C)	1	2	2	0.50000
KPI-7: Target IAQ class	1/2	1	1	0.25000
KPI-8: Target workplane illuminance (lux)	1/2	1	1	0.25000
			Consistency ratio	0.00000

(h) Comparisons with respect to "Investment cost ($)" node in "Health and Safety" cluster

	KPI-4: Ratio of actual to target no. of statutory orders removed (%)	KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	Priority vector
KPI-4: Ratio of actual to target no. of statutory orders removed (%)	1	2	0.66667
KPI-5: Ratio of actual to target no. of accidents per year reduced (%)	1/2	1	0.33333
		Consistency ratio	0.00000

(i) Comparisons with respect to "Investment cost ($)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	3	2	0.53961
KPI-7: Target IAQ class	1/3	1	1/2	0.16342
KPI-8: Target workplane illuminance (lux)	1/2	2	1	0.29696
			Consistency ratio	0.00885

(j) Comparisons with respect to "Payback period (year)" node in "Users' Perspective" cluster

	KPI-6 Target indoor air temperature (^{o}C)	KPI-7: Target IAQ class	KPI-8: Target workplane illuminance (lux)	Priority vector
KPI-6 Target indoor air temperature (^{o}C)	1	3	2	0.53961
KPI-7: Target IAQ class	1/3	1	1/2	0.16342
KPI-8: Target workplane illuminance (lux)	1/2	2	1	0.29696
			Consistency ratio	0.00885

(k) Comparisons with respect to “Target indoor air temperature (^{o}C)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

(l) Comparisons with respect to “Target IAQ class” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

(m) Comparisons with respect to “Target workplane illuminance (lux)” node in “Economic” cluster

	KPI-2: Payback Period	KPI-3: Investment Cost ($)	Priority vector
KPI-2: Payback Period	1	1/2	0.33333
KPI-3: Investment Cost ($)	2	1	0.66667
		Consistency ratio	0.00000

Appendix F.

Results of interviews - Weighted supermatrix and limit supermatrix

Appendix F - Weighted supermatrix and limit supermatrix (from the interviews)

Interviewee #1

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.052365	0.119244	0.078091	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.119244	0.000000	0.068250	0.092587	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.068250	0.318493	0.000000	0.329322	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.312507	0.129143	0.312507	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.071429	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.035714	0.062500	0.111111
	KPI-3	0.428571	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.214286	0.187500	0.222222
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.400000	0.000000	0.000000	0.000000	0.160000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.100000	0.000000	0.000000	0.000000	0.040000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.350487	0.000000	0.208338	0.034424	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.096440	0.000000	0.079496	0.145170	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.053073	0.000000	0.045500	0.020407	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #1

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131	0.073131
	Environmental	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249	0.074249
	Health and Safety	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413	0.167413
	Users' Perspective	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747	0.117747
Environmental (Env.)	KPI-1	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402	0.086402
Economic (Econ.)	KPI-2	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382	0.071382
	KPI-3	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456	0.081456
Health and Safety (H&S)	KPI-4	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997	0.119997
	KPI-5	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998	0.079998
Users' Perspective (U)	KPI-6	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568	0.070568
	KPI-7	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497	0.046497
	KPI-8	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159	0.011159

Interviewee #2

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.121318	0.037528	0.384620	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.124928	0.000000	0.295864	0.042000	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.327403	0.334708	0.000000	0.073380	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.047669	0.043973	0.166608	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.071429	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.125000	0.125000	0.111111
	KPI-3	0.428571	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.125000	0.125000	0.222222
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.400000	0.000000	0.000000	0.000000	0.022222	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.100000	0.000000	0.000000	0.000000	0.177778	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.352468	0.000000	0.083285	0.017589	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.042072	0.000000	0.031779	0.133883	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.105460	0.000000	0.218269	0.048527	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #2

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228	0.088228
	Environmental	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804	0.114804
	Health and Safety	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672	0.175672
	Users' Perspective	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535	0.063535
Environmental (Env.)	KPI-1	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277	0.098277
Economic (Econ.)	KPI-2	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226	0.082226
	KPI-3	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310	0.079310
Health and Safety (H&S)	KPI-4	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153	0.117153
	KPI-5	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243	0.090243
Users' Perspective (U)	KPI-6	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921	0.036921
	KPI-7	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135	0.025135
	KPI-8	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496	0.028496

Interviewee #3

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.035209	0.051017	0.086059	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.312507	0.000000	0.362924	0.051017	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.068250	0.375702	0.000000	0.362924	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.119244	0.089089	0.086059	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.416667	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.062500	0.041667	0.166667
	KPI-3	0.083333	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.187500	0.208333	0.166667
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.375000	0.000000	0.000000	0.000000	0.180000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.125000	0.000000	0.000000	0.000000	0.020000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.091477	0.000000	0.108504	0.035636	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.370922	0.000000	0.023377	0.150281	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.037600	0.000000	0.201453	0.014084	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #3

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089	0.063089
	Environmental	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788	0.141788
	Health and Safety	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064	0.181064
	Users' Perspective	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351	0.060351
Environmental (Env.)	KPI-1	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561	0.106561
Economic (Econ.)	KPI-2	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838	0.097838
	KPI-3	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267	0.055267
Health and Safety (H&S)	KPI-4	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622	0.119622
	KPI-5	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549	0.083549
Users' Perspective (U)	KPI-6	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107	0.028107
	KPI-7	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005	0.040005
	KPI-8	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757	0.022757

Interviewee #4

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.105460	0.105460	0.352468	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.048695	0.000000	0.042072	0.042072	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.284770	0.352468	0.000000	0.105460	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.166535	0.042072	0.352468	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.416667	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.041667	0.041667	0.055556
Economic (Econ.)	KPI-2	0.083333	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.208333	0.208333	0.277778
	KPI-3	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.033333	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.416667	0.000000	0.000000	0.000000	0.166667	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.352468	0.000000	0.219543	0.148369	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.042072	0.000000	0.026206	0.015040	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.105460	0.000000	0.087584	0.036591	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #4

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458	0.110458
	Environmental	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003	0.055003
	Health and Safety	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175	0.154175
	Users' Perspective	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923	0.109923
Environmental (Env.)	KPI-1	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003	0.105003
Economic (Econ.)	KPI-2	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266	0.073266
	KPI-3	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027	0.077027
Health and Safety (H&S)	KPI-4	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354	0.071354
	KPI-5	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128	0.112128
Users' Perspective (U)	KPI-6	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773	0.079773
	KPI-7	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421	0.028421
	KPI-8	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470	0.023470

Interviewee #5

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.758246	0.319618	0.558425	0.000000	1.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.088983	0.000000	0.121957	0.121957	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.587631	0.151247	0.000000	0.319618	0.000000	0.000000	0.000000	1.000000	1.000000	0.000000	0.000000	0.000000
	Users' Perspective	0.323386	0.090507	0.558425	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000	1.000000	1.000000
Environmental (Env.)	KPI-1	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	1.000000	0.000000	0.000000	1.000000	1.000000	1.000000
Economic (Econ.)	KPI-2	0.857143	0.000000	0.000000	0.000000	1.000000	0.000000	1.000000	0.000000	0.000000	0.200000	0.800000	0.800000
	KPI-3	0.142857	0.000000	0.000000	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.800000	0.200000	0.200000
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.200000	0.000000	0.000000	0.000000	0.200000	0.000000	1.000000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.800000	0.000000	0.000000	0.000000	0.800000	1.000000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.457934	0.000000	0.700973	0.443429	0.000000	0.000000	0.000000	1.000000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.126005	0.000000	0.106146	0.169200	0.000000	0.000000	1.000000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.416061	0.000000	0.192880	0.387371	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #5

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439	0.128439
	Environmental	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565	0.059565
	Health and Safety	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068	0.143068
	Users' Perspective	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309	0.098309
Environmental (Env.)	KPI-1	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263	0.078263
Economic (Econ.)	KPI-2	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889	0.125889
	KPI-3	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906	0.067906
Health and Safety (H&S)	KPI-4	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092	0.068092
	KPI-5	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138	0.102138
Users' Perspective (U)	KPI-6	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262	0.065262
	KPI-7	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261	0.029261
	KPI-8	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806	0.033806

Interviewee #6

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.166667	0.227273	0.166667	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.174182	0.000000	0.227273	0.166667	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.291075	0.166667	0.000000	0.166667	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.034744	0.166667	0.045455	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.450000	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.218750	0.031250	0.166667
	KPI-3	0.050000	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.031250	0.218750	0.166667
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.250000	0.000000	0.000000	0.000000	0.100000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.250000	0.000000	0.000000	0.000000	0.100000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.242205	0.000000	0.111111	0.066667	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.046209	0.000000	0.111111	0.066667	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.211586	0.000000	0.111111	0.066667	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #6

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491	0.117491
	Environmental	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355	0.112355
	Health and Safety	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761	0.149761
	Users' Perspective	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590	0.057590
Environmental (Env.)	KPI-1	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510	0.096510
Economic (Econ.)	KPI-2	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317	0.128317
	KPI-3	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788	0.061788
Health and Safety (H&S)	KPI-4	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238
	KPI-5	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238	0.087238
Users' Perspective (U)	KPI-6	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090	0.040090
	KPI-7	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061	0.031061
	KPI-8	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562	0.030562

Interviewee #7

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.091477	0.035065	0.091477	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.108583	0.000000	0.302179	0.037600	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.032885	0.037600	0.000000	0.370922	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.358533	0.370922	0.162756	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.428571	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.208333	0.214286	0.166667
	KPI-3	0.071429	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.041667	0.035714	0.166667
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.250000	0.000000	0.000000	0.000000	0.177778	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.250000	0.000000	0.000000	0.000000	0.022222	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.369797	0.000000	0.133333	0.052551	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.046906	0.000000	0.133333	0.131726	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.083297	0.000000	0.066667	0.015723	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #7

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155	0.077155
	Environmental	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947	0.100947
	Health and Safety	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379	0.126379
	Users' Perspective	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680	0.123680
Environmental (Env.)	KPI-1	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459	0.099459
Economic (Econ.)	KPI-2	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583	0.123583
	KPI-3	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905	0.054905
Health and Safety (H&S)	KPI-4	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017	0.077017
	KPI-5	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323	0.071323
Users' Perspective (U)	KPI-6	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309	0.077309
	KPI-7	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839	0.048839
	KPI-8	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404	0.019404

Interviewee #8

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.052365	0.091477	0.039308	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.071429	0.000000	0.037600	0.131376	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.214286	0.318493	0.000000	0.329315	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.214286	0.129143	0.370922	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.437500	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.208333	0.041667	0.166667
	KPI-3	0.062500	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.041667	0.208333	0.166667
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.050000	0.000000	0.000000	0.000000	0.028571	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.450000	0.000000	0.000000	0.000000	0.171429	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.375000	0.000000	0.079496	0.018182	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.062500	0.000000	0.045500	0.090909	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.062500	0.000000	0.208338	0.090909	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #8

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928	0.068928
	Environmental	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951	0.067951
	Health and Safety	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024	0.176024
	Users' Perspective	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356	0.124356
Environmental (Env.)	KPI-1	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142	0.080142
Economic (Econ.)	KPI-2	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196	0.101196
	KPI-3	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238	0.053238
Health and Safety (H&S)	KPI-4	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655	0.072655
	KPI-5	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665	0.124665
Users' Perspective (U)	KPI-6	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947	0.063947
	KPI-7	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203	0.033203
	KPI-8	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695	0.033695

Interviewee #9

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.375702	0.037528	0.037528	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.129142	0.000000	0.295864	0.166608	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.318493	0.035209	0.000000	0.295864	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.052365	0.089089	0.166608	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.416667	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.125000	0.050000	0.250000
	KPI-3	0.083333	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.125000	0.200000	0.083333
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.416667	0.000000	0.000000	0.000000	0.175000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.083333	0.000000	0.000000	0.000000	0.025000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.131376	0.000000	0.083285	0.042184	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.329315	0.000000	0.218269	0.140987	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.039308	0.000000	0.031779	0.016829	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #9

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555	0.104555
	Environmental	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487	0.117487
	Health and Safety	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135	0.142135
	Users' Perspective	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550	0.068550
Environmental (Env.)	KPI-1	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021	0.101021
Economic (Econ.)	KPI-2	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475	0.117475
	KPI-3	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748	0.066748
Health and Safety (H&S)	KPI-4	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548	0.103548
	KPI-5	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287	0.065287
Users' Perspective (U)	KPI-6	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413	0.038413
	KPI-7	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230	0.067230
	KPI-8	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551	0.007551

Interviewee #10

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.105460	0.048695	0.129142	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.148481	0.000000	0.284770	0.052365	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.081712	0.352468	0.000000	0.318493	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.269807	0.042072	0.166535	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.100000	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.062500	0.200000	0.066667
	KPI-3	0.400000	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.187500	0.050000	0.266667
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.400000	0.000000	0.000000	0.000000	0.150000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.100000	0.000000	0.000000	0.000000	0.050000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.105460	0.000000	0.064293	0.042184	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.352468	0.000000	0.233658	0.140987	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.042072	0.000000	0.035382	0.016829	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #10

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455	0.073455
	Environmental	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921	0.112921
	Health and Safety	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021	0.171021
	Users' Perspective	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776	0.080776
Environmental (Env.)	KPI-1	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166	0.098166
Economic (Econ.)	KPI-2	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420	0.086420
	KPI-3	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903	0.069903
Health and Safety (H&S)	KPI-4	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923	0.118923
	KPI-5	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059	0.080059
Users' Perspective (U)	KPI-6	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764	0.033764
	KPI-7	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960	0.066960
	KPI-8	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633	0.007633

Interviewee #11

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.166667	0.108583	0.166667	0.000000	0.333333	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.166667	0.000000	0.032885	0.166667	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.166667	0.166667	0.000000	0.166667	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.166667	0.166667	0.358533	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.200000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.416667	0.000000	0.000000	0.000000	0.500000	0.000000	0.200000	0.000000	0.000000	0.041667	0.041667	0.055556
	KPI-3	0.083333	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.000000	0.208333	0.208333	0.277778
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.428571	0.000000	0.000000	0.000000	0.175000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.071429	0.000000	0.000000	0.000000	0.025000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.032885	0.000000	0.085319	0.041018	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.108583	0.000000	0.223598	0.143331	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.358533	0.000000	0.024416	0.015651	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #11

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241	0.099241
	Environmental	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196	0.087196
	Health and Safety	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121	0.130121
	Users' Perspective	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908	0.113908
Environmental (Env.)	KPI-1	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784	0.094784
Economic (Econ.)	KPI-2	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776	0.109776
	KPI-3	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014	0.075014
Health and Safety (H&S)	KPI-4	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305	0.099305
	KPI-5	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822	0.060822
Users' Perspective (U)	KPI-6	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979	0.029979
	KPI-7	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161	0.055161
	KPI-8	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694	0.044694

Interviewee #12

(a) Weighted supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.000000	0.274973	0.100000	0.221715	0.200000	0.000000	0.333333	0.000000	0.000000	0.000000	0.000000	0.000000
	Environmental	0.159809	0.000000	0.200000	0.084600	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	Health and Safety	0.060979	0.104922	0.000000	0.193686	0.000000	0.000000	0.000000	0.500000	0.500000	0.000000	0.000000	0.000000
	Users' Perspective	0.279212	0.120105	0.200000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Environmental (Env.)	KPI-1	0.000000	0.500000	0.000000	0.000000	0.200000	0.000000	0.000000	0.000000	0.000000	0.250000	0.250000	0.333333
Economic (Econ.)	KPI-2	0.166667	0.000000	0.000000	0.000000	0.200000	0.500000	0.000000	0.000000	0.000000	0.083333	0.083333	0.111111
	KPI-3	0.333333	0.000000	0.000000	0.000000	0.000000	0.000000	0.333333	0.000000	0.000000	0.166667	0.166667	0.222222
Health and Safety (H&S)	KPI-4	0.000000	0.000000	0.375000	0.000000	0.133333	0.000000	0.000000	0.000000	0.500000	0.000000	0.000000	0.000000
	KPI-5	0.000000	0.000000	0.125000	0.000000	0.066667	0.000000	0.000000	0.500000	0.000000	0.000000	0.000000	0.000000
Users' Perspective (U)	KPI-6	0.000000	0.000000	0.000000	0.250000	0.107923	0.000000	0.179872	0.000000	0.000000	0.000000	0.250000	0.000000
	KPI-7	0.000000	0.000000	0.000000	0.125000	0.032685	0.000000	0.054475	0.000000	0.000000	0.250000	0.000000	0.000000
	KPI-8	0.000000	0.000000	0.000000	0.125000	0.059392	0.000000	0.098987	0.000000	0.000000	0.000000	0.000000	0.000000

Interviewee #12

(b) Limit supermatrix

Clusters	Nodes	(Econ.)	(Env.)	(H&S)	(U)	KPI-1	KPI-2	KPI-3	KPI-4:	KPI-5:	KPI-6	KPI-7	KPI-8
Categories	Economic	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401	0.113401
	Environmental	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502	0.100502
	Health and Safety	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391	0.111391
	Users' Perspective	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180	0.100180
Environmental (Env.)	KPI-1	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251	0.103251
Economic (Econ.)	KPI-2	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748	0.100748
	KPI-3	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162	0.094162
Health and Safety (H&S)	KPI-4	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903	0.085903
	KPI-5	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153	0.063153
Users' Perspective (U)	KPI-6	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508	0.062508
	KPI-7	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715	0.036715
	KPI-8	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088	0.028088

Appendix G.

Results of interviews - Global priority vectors and renormalized relative weights of KPIs

Global priority vectors and renormalized relative weights of KPIs (from the interviews)

Interviewee #1-4

KPIs		Interviewee No.							
		1		2		3		4	
		Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight
1	Energy saving (%)	0.086402	0.152261	0.098277	0.176199	0.106561	0.192451	0.077027	0.135030
2	Payback period (year)	0.071382	0.125792	0.082226	0.147422	0.097838	0.176697	0.105003	0.184073
3	Investment cost ($)	0.081456	0.143545	0.07931	0.142194	0.055267	0.099813	0.073266	0.128437
4	Ratio of actual to target no. of statutory orders removed (%)	0.119997	0.211464	0.117153	0.210042	0.119622	0.216039	0.071354	0.125085
5	Ratio of actual to target no. of accidents per year reduced (%)	0.079998	0.140976	0.090243	0.161795	0.083549	0.150891	0.112128	0.196563
6	Target indoor air temperature (^oC)	0.070568	0.124358	0.036921	0.066195	0.028107	0.050762	0.079773	0.139844
7	Target IAQ class	0.046497	0.081939	0.025135	0.045064	0.040005	0.07225	0.028421	0.049823
8	Target workplane illuminance (lux)	0.011159	0.019665	0.028496	0.05109	0.022757	0.041099	0.02347	0.041144

Interviewee #5-8

KPIs		Interviewee No.							
		5		6		7		8	
		Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight
1	Energy saving (%)	0.078263	0.137155	0.096510	0.171481	0.099459	0.173928	0.080142	0.142414
2	Payback period (year)	0.125889	0.220619	0.128317	0.227996	0.123583	0.216115	0.101196	0.179827
3	Investment cost ($)	0.067906	0.119005	0.061788	0.109786	0.054905	0.096015	0.053238	0.094605
4	Ratio of actual to target no. of statutory orders removed (%)	0.068092	0.119330	0.087238	0.155006	0.077017	0.134683	0.072655	0.129109
5	Ratio of actual to target no. of accidents per year reduced (%)	0.102138	0.178996	0.087238	0.155006	0.071323	0.124726	0.124665	0.221532
6	Target indoor air temperature (ºC)	0.065262	0.114371	0.040090	0.071233	0.077309	0.135194	0.063947	0.113635
7	Target IAQ class	0.029261	0.051280	0.031061	0.055190	0.048839	0.085407	0.033203	0.059002
8	Target workplane illuminance (lux)	0.033806	0.059245	0.030562	0.054303	0.019404	0.033933	0.033695	0.059877

Interviewee #9-12

KPIs		Interviewee No.							
		9		10		11		12	
		Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight	Global priority vector	Renormalized relative weight
1	Energy saving (%)	0.101021	0.178082	0.098166	0.174726	0.094784	0.166423	0.103251	0.179714
2	Payback period (year)	0.117475	0.207087	0.086420	0.153819	0.109776	0.192747	0.100748	0.175358
3	Investment cost ($)	0.066748	0.117665	0.069903	0.124421	0.075014	0.131711	0.094162	0.163895
4	Ratio of actual to target no. of statutory orders removed (%)	0.103548	0.182536	0.118923	0.211672	0.099305	0.174362	0.085903	0.149519
5	Ratio of actual to target no. of accidents per year reduced (%)	0.065287	0.115089	0.080059	0.142497	0.060822	0.106792	0.063153	0.109922
6	Target indoor air temperature (°C)	0.038413	0.067715	0.033764	0.060097	0.029979	0.052638	0.062508	0.108799
7	Target IAQ class	0.067230	0.118514	0.066960	0.119182	0.055161	0.096853	0.036715	0.063905
8	Target workplane illuminance (lux)	0.007551	0.013311	0.007633	0.013586	0.044694	0.078475	0.028088	0.048889

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